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AFML-TR-74-193

(2)

VALIDATION OF REDUCED COMPOSITE ALLOWABLE VARIATION VIA PRESTRESSING

NOVEMBER 1974

TECHNICAL REPORT AFML-TR-74-193
FINAL REPORT FOR PERIOD JULY 1973 - JUNE 1974

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three types of boron/epoxy prepreg tape were prestressed to fracture weak sites along the fiber by winding over 0.3- to 0.6-inch diameter rollers prior to lamination. The prestressed prepreg was then laminated, and design allowable testing was conducted to determine if mechanical strength properties are increased and data scatter is reduced by prestressing. The types of prepreg studied were: standard "Rigidite" 5505/4 prepreg, carbon substrate boron fiber prepreg, and a prepreg made from "defect" tungsten substrate boron that was

Next Page

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20. Abstract (Cont.)

manufactured in a high-speed, low-cost production process. The strength of angleply composites of both "Rigidite" 5505/4 and carbon substrate boron composites were unaffected by prestressing. A study was made to determine if prepreg costs could be reduced by manufacturing low-cost "defect" boron fiber and prestressing it to improve its properties. The results of this study were inconclusive. The test results show prestressing marginally improved some composite properties while others were reduced. On "Rigidite" 5505/4 unidirectional composites, fatigue strength was significantly improved by prestressing, while longitudinal tensile strength was reduced at room temperature and 350F. On unidirectional carbon substrate boron composites, the longitudinal tensile strength at room temperature and 350F was increased with attendant variability, while fatigue strength at high stress levels was reduced but not affected at low stress levels.

SUMMARY

Prestressing experiments were conducted on three types of boron/epoxy prepreg to determine if prestressing could increase composite allowable design properties by reducing data scatter. Prestressing is a process which selectively fractures weak sites on the fiber within prepreg prior to laminating the prepreg into composite structures. The types of prepreg used included:

1. "Rigidite" 5505/4 production grade prepreg manufactured by Avco Corporation.
2. Prepreg made from a substandard tungsten substrate boron fiber, a fiber manufactured in a low-cost process by Avco Corporation. This "defect" fiber had lower strength than commercial grade fiber. This prepreg was investigated to determine if prestressing could improve its properties to the level of commercial fiber.
3. Prepreg made from carbon substrate boron fiber. This is an experimental fiber under Air Force development.

The program had two objectives:

1. Determine if design allowable properties can be improved by prestressing, and if data scatter can be reduced. Design allowable properties included tension, compression, in-plane shear, and tension-tension fatigue.
2. Determine if prestressing could have an economic impact on the cost of boron/epoxy prepreg by upgrading defect fiber which can be made at lower cost.

Prestressing doesn't significantly alter composite properties and the cost study was inconclusive. There was some improvement in selected design allowable properties due to prestressing. Carbon substrate boron was more amenable than standard boron to prestressing. There was some increase in longitudinal tensile strength of unidirectional composites both at room temperature and at 350F.

The fatigue strength of standard boron was significantly improved by prestressing. The increase in fatigue strength was surprisingly large. For example, at a nominal load of 165 ksi the fatigue life was increased from 25,500 cycles to failure (unstressed) to 1,758,000 cycles to failure (prestressed).

There was no consistent trend in the data showing mechanical property reduction due to prestressing. However, several properties were lowered. The fatigue strength of carbon substrate boron was reduced at high stress levels but not at low stress levels. Longitudinal tensile properties of unidirectional standard boron composites were reduced but longitudinal tensile strength of angleply composites was not.

Conventional fabrication and cure procedures were used to cure both prestressed and unstressed laminates. Thicknesses of the cured laminates ranged between 4.9 and 5.2 mills per ply. Boron fiber volumes varied between 47% and 49%.

The question of the economic impact of prestressing on boron/epoxy prepreg could not be resolved in this program. A defect boron fiber prepreg amenable to prestressing could not be obtained. This does not preclude the possibility that a defect fiber could be improved by prestressing.

In this program, it was discovered that certain boron/epoxy ply orientations are susceptible to severe degradation due to saw cutting when using machining procedures common to the industry. For example, the longitudinal tensile strength of the $[0°/\pm45°/90°]_s$ orientation can be degraded by 50 percent in strength and in strain to failure by saw cutting perpendicular to the 0° fiber direction. Other orientations, e.g. unidirectional and $[0°/\pm45°]_s$ laminates, are not degraded by saw cutting.

PREFACE

This report was prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California, under USAF Contract F33615-73-C-5068, Project No. 6169CW, and was administered under the direction of the Air Force Materials Laboratory. Mr. Robert Neff and Lt. Gary Hollingsworth (AFML/LC) acted as program monitors.

Mr. D. J. Crabtree served as the principal investigator in the final phases of this program. Mr. B. B. Bowen was the principal investigator in the earlier phases of the program. Other Northrop personnel who made major contributions in this research program were Messrs. J. Nemo, G. Brown, D. Waterman, Dr. G. H. Bischoff, and Dr. G. J. Mills.

The contractor's report number is NOR 74-222. This report covers work from July 1973 to June 1974.

This report was submitted by the author 1 August 1974.

TABLE OF CONTENTS

CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

TABLES (Continued)

SECTION I

INTRODUCTION

The strength of boron fibers used in boron/epoxy prepreg follows a gaussian distribution with a spread in the currently used fiber ranging from 410-620 ksi[1]. Previous work conducted at Northrop[1,2] has shown that prestressing boron/epoxy prepreg by passing it over 0.3- to 0.6-inch diameter rollers fractures the weakest sites along the boron fiber, thereby removing the low strength "tail" on the gaussian curve. Composites cured from the prestressed prepreg had higher tensile strengths and reduced data scatter compared to composites cured from unstressed prepreg. The presence of broken fibers (from prestressing) had no deleterious effect upon composite properties. However, testing was confined to filament testing and to unidirectional composite tension testing at ambient temperature. The effect of prestressing upon angleply properties, compression, shear, and upon mechanical properties at elevated temperatures was not determined.

This program was initiated to determine the effect of prestressing on a full range of composite engineering properties at room temperature and at 350F. The objective was to determine if prestressing increases composite mechanical properties and decreases data scatter in these properties enough to have an impact on engineering design allowables. A second objective of the program was to determine if prestressing can have an impact on boron/epoxy material costs. Specifically, the objective was to determine if the low strength boron fibers which could be produced at much lower costs by accelerating the production process could be upgraded by prestressing to the strength obtained with fibers used commercially at this time. A full discussion of the experimental work done against these two objectives is presented in Section II.

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(1) Air Force Contract No. F33615-71-C-1567, "Increasing Strengths of Boron Fiber and Graphite Fiber Plastic Composites."

(2) Air Force Contract No. F33615-72-C-1614, "Investigation of Prestressing of Prepreg."

Serious problems were encountered during the program in obtaining acceptable tensile strength and strain-to-failure values with the 0°/+45°/-45°/90°/90°/-45°/+45°/0° angleply composites. An acceptable room temperature strength for this orientation is 60-70 ksi and an acceptable strain is 6,000 μ in/in. Strengths in the range of 20-30 ksi and strains of 3,000 μ in/in. were being consistently obtained early in the program. The problem was resolved, and the cause found to be a degradative effect upon specific angleply orientations caused by sawing the composite with diamond cutting wheels standard to the industry. Unidirectional composites are not degraded by saw cutting, nor are all angleply orientations. A full discussion of the problem and the experiemental evidence justifying our identification of the degradative effect of saw cutting is presented in Section II of this report.

SECTION II
TECHNICAL DISCUSSION

A. PRESTRESSING OF BORON/EPOXY PREPREG

Prestressing is a method of breaking flaws in boron fibers in a prepreg tape prior to the lamination of the prepreg into composite structures. Defects along the fibers determine the fiber strength statistics and thereby the composite strength statistics.

Low strength flaws along the fibers act as sites for crack initiation and ultimate degradation of properties substantially below the strength potential of the fibers. Prestressing purposely breaks the fibers at these weak sites, thus precluding crack initiation at low stress levels in the composite and affecting an increase in fiber strength. The most effective way to stress the fibers is to apply a continuous bending stress along the length of the fibers. To accomplish this, the prepreg is run through a series of rollers while under a tension load. Reverse bending of the boron fibers is necessary to increase the effectiveness of the selective breaking process. Figure 1 is a schematic of the prestressing machine that was used in this program. Supply and pickup reels are those upon which the prepreg is shipped by the suppliers, each driven by synchronous motors. The tension load, $W = \sim 45$ pounds, is applied to provide a uniform tension on the tape for alignment and roller contact. Four teflon-coated rollers subject the tape to alternate bend stressing.

Figure 2 shows four views of the prestressing machine. It has an additional feature for roller stressing a stationary, 3-foot length section of tape by moving the roller assembly along fixed rails. Rollers of interchangeable diameter can be used and the contact angle, tension load and feed rate can be varied as process parameters. Generally, the roller diameter varies between 0.3- to 0.6-inch.

Once the prepreg tape has been prestressed, it is layed up and cured in the conventional way. The broken fibers are left in the tape. Since the broken fibers are longer than the critical length, the fibers, although broken, still function as continuous fibers.

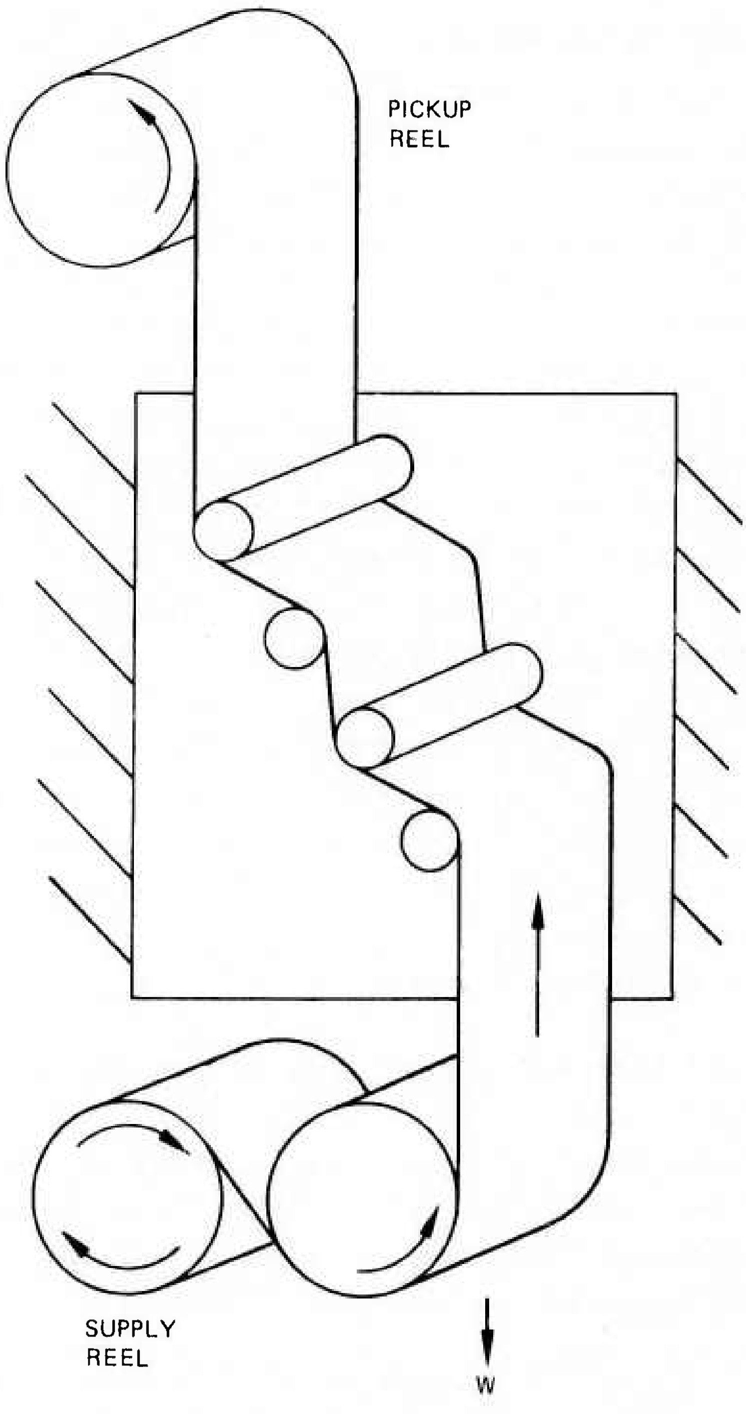


FIGURE 1. SCHEMATIC OF PRESTRESSING MACHINE

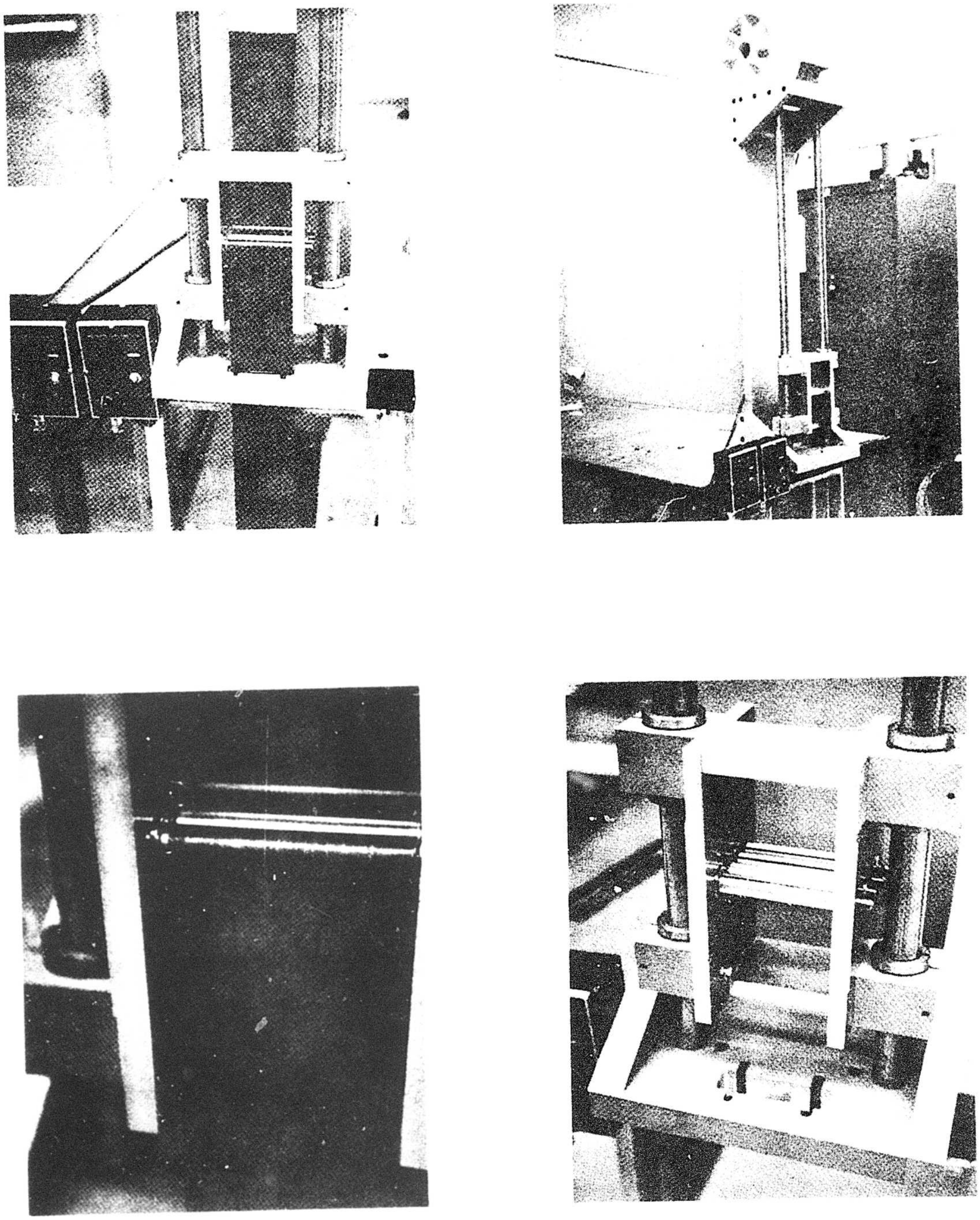


FIGURE 2. PREPREG TAPE PROCESSING IN THE PRESTRESSING MACHINE

Prestressing is a very simple operation and if incorporated into the prepreg process would not increase prepreg costs. The rollers would be placed at the end of the prepreg manufacturing line and prepreg would be wound through the rollers just before being wound onto spools and packaged.

B. EXPERIMENTAL PROCEDURES

Design allowable testing was conducted on three types of boron/epoxy prepreg: (1) "specification" grade tungsten substrate boron,"Rigidite" 5505/4, purchased from Avco Corporation. This prepreg was taken from Avco's production line and is typical of boron/epoxy prepreg used throughout the industry at this time; (2) "non-specification" grade tungsten substrate boron purchased from Avco. Avco produced the boron fiber used in this prepreg in high speed production runs; it was intended to be a highly flawed fiber, producible at reduced cost, whose strength could be upgraded by prestressing; and (3) carbon substrate boron. This was an experimental material still under development by the Air Force.

The design allowable testing program included both uniaxial and angleply testing. The orientation used for all angleply testing was $[0°/\pm45°/90°]_s$. For angleply tensile tests 8-ply laminates were tested. For in-plane shear on angleply composites 16-ply laminates were tested. The design allowable testing plan used is shown in Table 1. The testing program is summarized in the Flow Chart shown in Figure 3.

The prepreg was first analyzed by standard quality control tests. These tests included 0° and 90° flexural strength and modulus at ambient temperatures, and short beam shear strength at ambient temperature. Following the receiving inspection tests (all prepreg used in the program passed these tests), the material was characterized for filament strength and prestressing parameters were established. A 6-inch length was sampled from each roll and a random batch of 100 filaments were tested in tension using a 3-inch gage length. The strength distribution curve was plotted and the standard deviation calculated. This procedure was repeated after prestressing with various selected roller sizes and the distribution curves compared with the unstressed standard for selection of optimum prestress parameters. Final

TABLE 1
DESIGN ALLOWABLE TEST PLAN

TEST	SPECIMEN THICKNESS	NO. SPECIMENS	TEST TEMP.	PRESTRESS
0° Tension	8 Plies	10	R.T.	No
0° Tension	8 Plies	10	R.T.	Yes
0° Tension	8 Plies	5	350F	No
0° Tension	8 Plies	5	350F	Yes
90° Tension	15 Plies	5	R.T.	No
90° Tension	15 Plies	5	R.T.	Yes
0° Compression	8 Plies	5	R.T.	No
0° Compression	8 Plies	5	R.T.	Yes
0° Compression	8 Plies	3	350F	No
0° Compression	8 Plies	3	350F	Yes
$[0°/\pm45°/90°]_s$ Tension	8 Plies	5	R.T.	No
$[0°/\pm45°/90°]_s$ Tension	8 Plies	5	R.T.	Yes
$[0°/\pm45°/90°]_s$ Tension	8 Plies	5	350F	No
$[0°/\pm45°/90°]_s$ Tension	8 Plies	5	350F	Yes
$[0°/\pm45°/90°]_s$ Rail Shear	16 Plies	3	R.T.	No
$[0°/\pm45°/90°]_s$ Rail Shear	16 Plies	3	R.T.	Yes
0° Tensile Fatigue (R=0.1)	8 Plies	15	R.T.	No
0° Tensile Fatigue (R=0.1)	8 Plies	15	R.T.	Yes

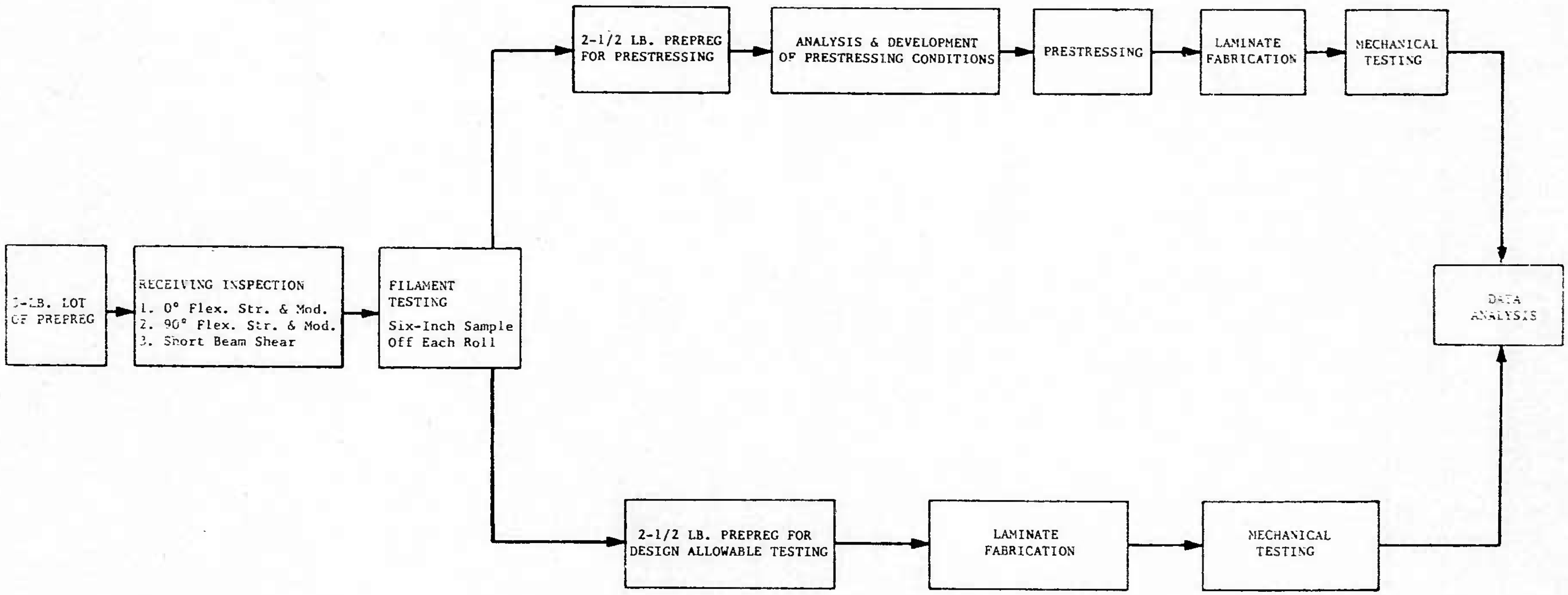


FIGURE 3. PROGRAM FLOW CHART

selection was determined by prestressing six-foot lengths, fabricating eight-ply unidirectional laminates, and comparing unstressed versus prestressed composite ultimate strengths and standard deviations. A more complete description of the filament testing procedures that were used is presented in the Appendix. After prestressing parameters were established, the prepreg was divided into two lots. One lot was used to obtain design allowable test data on the unstressed prepreg; the other lot was prestressed and then used for design allowable testing.

A complete description of the procedures used to fabricate laminates and to determine mechanical strength properties is presented in the Appendix.

C. DESIGN ALLOWABLE TESTING OF "SPECIFICATION" GRADE TUNGSTEN SUBSTRATE BORON/EPOXY

Analysis of Prepreg

A five-pound batch of "Rigidite" 5505/4 prepreg was used for design allowable testing. This material arrived in one roll. Inspection of the tape showed two gaps, each 0.020-inch wide, apparently running the length of the roll. A question arose as to the acceptability of the tape because of these gaps. However, the tape proved to be acceptable. Test results obtained from the quality control laminate are shown in Table 2.

The longitudinal flexural and interlaminar shear properties were fully acceptable, while transverse flexural was marginal. Several points can be made regarding this: (1) this tape, despite the gaps, passes the General Dynamics specification which calls for 209 fibers/inch width and the Grumman specification which allows 0.030-inch gaps; (2) the transverse flex properties obtained here are the minimum which can be realized because the quality control panel was laid up without taking care to prevent stacking the gap areas. The average filament tensile strength was 467 ksi.

TABLE 2
QUALITY CONTROL ANALYSIS OF
STANDARD BORON/EPOXY PREPREG

TEST	Q.C. TEST RESULTS	SPEC. MINIMUM
Longitudinal Flexural Strength (3 specimens)	272 - 278 ksi	225 ksi (G.D.)
Transverse Flexural Strength (3 specimens)	11.7 - 12.0	11.0 (Grumman) 13.0 (G.D.)
Short Beam Shear (3 specimens)	15.8 - 16.2	13.0 (G.D.)
Longitudinal Tensile Strength (5 specimens)	Avg. 209 C.V. 7%	Not Specified

Selection of Prestressing Conditions

Tests were run to select the optimum prestressing conditions for the prepreg. Prepreg was prestressed using three different roller diameters. Laminates $(0°)_8$ were fabricated from each material and longitudinal tensile strength was determined at room temperature. A summary of the data is presented in Table 3.

TABLE 3
PRESTRESSING OF "RIGIDITE" 5505/4

	PRESTRESS NO. 1	PRESTRESS NO. 2	PRESTRESS NO. 3	UNSTRESSED
Roller Diameter	0.475-inch	0.525-inch	0.575-inch	-
Load	40 lbs.	40 lbs.	40 lbs.	-
Mean, Longitudinal Tensile Str., ksi	205	202	209	205
Number of Specimens	5	5	5	5
Standard Deviation	5	11	5	7
Coefficient of Variation	2.5%	5.5%	2.5%	3.4%

All standard boron/epoxy prepreg used subsequently in the program was prestressed over the 0.575-inch roller using 40-lb. load. These conditions gave the maximum longitudinal tensile strength and the lower coefficient of variation in tensile strength data. Mechanical strength properties are presented in Tables 4 through 11. Fatigue data is presented in Table 40.

TABLE 4
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	66.0	7430	10.51	-	Strain Gage
2	62.3	6850	10.65	-	"
3	67.7	7420	10.66	-	"
4	64.9	6800	10.77	-	"
5	64,9	6690	11.05	-	"
Mean	65.2	7040	10.73		
Std. Dev.	2.0	360	0.20		
Coeff. of Variation	3.1%	5.1%	1.9%		

PRESTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	63.7	6880	11.47	0.36	Strain Gage
2	54.1	5430	11.10	0.27	"
3	59.6	6160	11.29	0.29	"
4	58.5	6070	11.58	0.35	"
5	61.5	6400	11.43	0.32	"
6	69.1	7540	11.18	-	Extensometer
7	66.4	7220	10.89	-	"
Mean	61.8	6530	11.28	0.32	
Std. Dev.	5.0	730	0.24	-	
Coeff. of Variation	8.1%	11.2%	2.1%	-	

TABLE 5
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ 350F
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	59.9	8140	8.73
2	57.3	7380	8.95
3	56.9	8480	7.59
4	55.3	7560	8.34
5	57.4	8080	8.06
Mean	57.4	7930	8.33
Std. Dev.	1.6	450	0.54
Coeff. of Variation	2.8%	5.7%	6.5%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	55.1	5990	9.69
2	46.3	5140	9.31
3	60.9	7220	9.62
4	66.3	7980	9.43
5	62.7	7780	10.49
Mean	58.3	6820	9.71
Std. Dev.	7.8	1220	0.46
Coeff. of Variation	13.4%	17.9%	4.7%

TABLE 6
UNIDIRECTIONAL
LONGITUDINAL TENSILE PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	221	7610	29.00	0.17	Strain Gage
2	240	8180	31.17	0.18	"
3	221	8000	31.01	0.18	"
4	215	7360	30.33	-	Extensometer
5	223	7520	31.20	-	"
6	218	7320	30.73	-	"
7	223	7720	29.52	-	"
8	228	7860	30.73	-	"
9	205	6720	32.05	-	"
10	218	7620	29.64	-	"
Mean	221	7590	30.54	0.18	
Std. Dev.	9	410	0.92	-	
Coeff. of Variation	4.1%	5.4%	3.0%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	216	7380	30.07	0.22	Strain Gage
2	210	7160	30.11	0.22	"
3	216	7390	29.97	0.21	"
4	210	6760	32.25	-	Extensometer
5	214	7140	31.01	-	"
6	198	6300	33.11	-	"
7	218	7160	32.67	-	"
8	220	7740	29.26	-	"
9	211	7160	30.45	-	"
10	188	6580	28.64	-	"
Mean	210	7080	30.75	0.22	
Std. Dev.	10	420	1.48	-	
Coeff. of Variation	4.8%	5.9%	4.8%	-	

TABLE 7
UNIDIRECTIONAL
LONGITUDINAL TENSILE PROPERTIES
$(0°)_8$ @ 350F
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	213	7400	30.04	0.19	Strain Gage
2	193	6720	29.21	-	Extensometer
3	197	7900	25.42	-	"
4	204	7560	26.82	-	"
5	195	6880	29.82	-	"
Mean	200	7300	28.26	0.19	
Std. Dev.	8	490	2.04	-	
Coeff. of Variation	4.0%	6.7%	7.2%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	172	6040	30.04	0.08	Strain Gage
2	155	6480	29.56	-	Extensometer
3	165	5400	28.89	-	"
4	178	4340	33.92	-	"
5	183	7660	26.14	-	"
Mean	171	5980	29.71	0.08	
Std. Dev.	11	1240	2.80	-	
Coeff. of Variation	6.4%	20.7%	9.4%	-	

TABLE 8
UNIDIRECTIONAL
LONGITUDINAL COMPRESSION PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	277	8430	32.25
2	297	9060	33.11
3	278	8660	31.38
4	280	8540	32.13
5	288	8790	32.23
Mean	284	8700	32.22
Std. Dev.	8	240	0.61
Coeff. of Variation	2.8%	2.8%	1.9%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	290	--	33.10
2	297	8890	33.73
3	284	8540	33.15
4	291	8910	31.77
5	277	8180	33.05
Mean	288	8630	32.96
Std. Dev.	8	340	0.72
Coeff. of Variation	2.8%	3.9%	2.2%

TABLE 9
UNIDIRECTIONAL
LONGITUDINAL COMPRESSION PROPERTIES
$(0°)_8$ @ 350F
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	140	-	33.34
2	140	4160	33.47
3	137	3950	31.80
Mean	139	4060	32.87
Std. Dev.	2	148	0.93
Coeff. of Variation	1.4%	3.6%	2.8%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	137	4130	32.66
2	140	3880	35.43
3	122	3500	34.13
Mean	133	3840	34.07
Std. Dev.	10	320	1.38
Coeff. of Variation	7.5%	8.3%	4.0%

TABLE 10
UNIDIRECTIONAL
TRANSVERSE TENSILE PROPERTIES
$(0°)_{15}$ @ ROOM TEMPERATURE
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	7.0	2740	2.73	0.02	Strain Gage
2	8.1	3480	2.76	-	Extensometer
3	8.2	3440	2.81	-	"
4	7.3	3100	2.74	-	"
5	7.4	3140	2.73	-	"
Mean	7.6	3180	2.75	0.02	
Std. Dev.	0.5	300	0.03	-	
Coeff. of Variation	6.6%	9.4%	1.1%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	8.1	3300	2.79	0.04	Strain Gage
2	8.5	3680	2.77	-	Extensometer
3	8.6	3740	2.82	-	"
4	8.5	3800	2.66	-	"
5	8.6	3680	2.72	-	"
Mean	8.5	3640	2.75	0.04	
Std. Dev.	0.2	200	0.06	-	
Coeff. of Variation	2.4%	5.5%	2.2%	-	

TABLE 11
RAIL SHEAR PROPERTIES
$[0°/\pm45°/90°]_{2s}$ - 16-PLY @ ROOM TEMPERATURE
"RIGIDITE" 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	29.4	13,130	3.86
2	25.7	12,980	6.01
3	23.9	12,190	4.85
Mean	26.3	12,770	4.91
Std. Dev.	2.8	500	1.07
Coeff. of Variation	10.6%	3.9%	21.8%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	23.7	11,860	4.31
2	27.2	12,370	3.97
3	37.7	13,000	4.47
Mean	29.5	12,410	4.25
Std. Dev.	7.3	570	0.26
Coeff. of Variation	24.7%	4.6%	6.1%

D. DESIGN ALLOWABLE TESTING OF CARBON SUBSTRATE BORON/EPOXY

Carbon substrate boron is an experimental material under Air Force development. The tensile strength of the fiber is considerably below the strength of standard boron fiber. The fiber was used in this program to see if prestressing could improve its strength. The Air Force supplied all the carbon substrate fiber used in the program. Avco Corporation fabricated a conventional prepreg from the fiber using 104 fiberglass scrim cloth and Narmco 2387 resin. The same scrim cloth and resin is used in "Rigidite" 5505/4 prepreg.

Receiving and Inspection Analysis of Prepreg

Since this is a material under development, it has no specification. However, a unidirectional laminate was prepared from it and receiving inspection tests were run. The material passed the receiving inspection tests established for "Rigidite" 5505/4. Data is presented in Table 12.

TABLE 12
QUALITY CONTROL ANALYSIS OF
CARBON SUBSTRATE BORON/EPOXY PREPREG

TEST	TEST RESULTS	SPEC. MINIMUM (TUNGSTEN CORE BORON)
Longitudinal Flexural Strength, ksi (3 specimens)	242 - 264	225
Longitudinal Flexural Modulus, msi (3 specimens)	24.95 - 26.55	-
Transverse Flexural Strength, ksi (3 specimens)	10.1 - 12.8	13.0
Transverse Flexural Modulus, msi (3 specimens)	2.23 - 2.37	-
Short Beam Shear, ksi	14.7 - 15.3	13.0

The prepreg was analyzed using the experimental program shown in Figure 3. The prepreg was prestressed using a 0.560-inch roller and a load of 45 pounds. Design allowable data is presented in Tables 13 through 20. Fatigue data is presented in Table 41.

TABLE 13
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm 45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	59.4	7890	10.31	0.28	Strain Gage
2	59.0	8040	9.06	-	Extensometer
3	59.6	7460	9.11	-	"
4	53.6	7260	8.19	-	"
5	50.5	6080	8.80	-	"
6	59.0	-	-	-	-
Mean	56.8	7350	9.09	0.28	
Std. Dev.	3.8	780	0.77	-	
Coeff. of Variation	6.7%	10.6%	8.5%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	53.5	7180	8.96	-	Strain Gage
2	55.1	6910	9.08	-	"
3	49.0	5840	9.11	-	"
4	56.5	7020	9.09	0.31	"
5	46.7	5480	9.12	-	"
6	55.5	-	-	-	-
Mean	52.7	6480	9.07	0.31	
Std. Dev.	4.0	780	0.06	-	
Coeff. of Variation	7.6%	12.0%	0.7%	-	

TABLE 14
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ 350F
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	53.6	7,060	8.77
2	54.6	6,760	8.76
3	41.1	4,920	8.61
4	53.9	-	8.71
5	54.5	6,280	9.42
Mean	51.5	6,260	8.85
Std. Dev.	5.8	950	0.32
Coeff. of Variation	11.3%	15.2%	3.6%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	53.8	7,090	8.62
2	49.5	6,280	8.15
3	48.7	6,320	8.44
4	50.0	7,000	8.17
5	51.9	5,890	9.37
Mean	50.8	6,520	8.55
Std. Dev.	2.0	510	0.55
Coeff. of Variation	3.9%	7.8%	5.8%

TABLE 15
UNIDIRECTIONAL
LONGITUDINAL TENSILE PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	170	6800	28.26	0.21	Strain Gage
2	172	6750	25.94	0.18	"
3	171	6660	27.11	0.20	"
4	157	6160	26.25	-	Extensometer
5	170	6300	28.75	-	"
6	165	6620	25.69	-	"
7	176	6380	29.96	-	"
8	165	6380	29.03	-	"
9	153	6160	28.14	-	"
10	154	6180	26.12	-	"
Mean	165	6440	27.52	0.19	
Std. Dev.	8	250	1.50	-	
Coeff. of Variation	4.8%	3.9%	5.4%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	195	7610	27.72	0.21	Strain Gage
2	195	7640	27.97	0.24	"
3	183	7120	27.36	0.18	"
4	197	7780	27.60	-	Extensometer
5	176	6820	27.41	-	"
6	192	7640	26.71	-	"
7	193	7700	27.22	-	"
8	188	7660	26.17	-	"
9	183	7340	27.08	-	"
10	160	6960	24.44	-	"
Mean	186	7430	26.97	0.21	
Std. Dev.	11	340	1.03	-	
Coeff. of Variation	5.9%	4.6%	3.8%	-	

TABLE 16
UNIDIRECTIONAL
LONGITUDINAL TENSILE PROPERTIES
$(0°)_8$ @ 350F
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	INSTRU-MENTATION
1	110	6,200	25.40	Strain Gage
2	110	4,220	30.57	Extensometer
3	135	6,380	23.76	"
4	138	7,360	22.84	"
5	133	6,160	26.70	"
Mean	125	6,060	25.85	
Std. Dev.	14	1,140	3.02	
Coeff. of Variation	11.2%	18.8%	11.7%	

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	INSTRU-MENTATION
1	159	6,380	27.18	Strain Gage
2	160	5,800		Extensometer
3	168	6,500	29.70	"
4	136	4,440		"
5	155	6,060	28.14	"
Mean	155	5,840	28.34	
Std. Dev.	12	830	1.27	
Coeff. of Variation	7.7%	14.2%	4.5%	

TABLE 17
UNIDIRECTIONAL
LONGITUDINAL COMPRESSION PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	276	9,850	27.35
2	235	8,150	28.62
3	273	9,730	27.73
4	269	10,600	28.16
5	265	9,350	28.14
Mean	264	9,540	28.00
Std. Dev.	16	900	0.48
Coeff. of Variation	6.1%	9.4%	1.7%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	281	9,780	28.10
2	247	8,720	27.79
3	292	10,550	27.28
4	258	9,080	27.99
5	292	10,200	28.43
Mean	274	9,700	27.92
Std. Dev.	20	760	0.42
Coeff. of Variation	7.3%	7.8%	1.5%

TABLE 18
UNIDIRECTIONAL
LONGITUDINAL COMPRESSION PROPERTIES
$(0°)_8$ @ 350F
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	166	5580	29.80
2	141	4780	28.73
3	135	4570	28.88
Mean	147	4980	29.14
Std. Dev.	16	530	0.58
Coeff. of Variation	10.9%	10.6%	2.0%

PRESTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	145	5010	28.78
2	127	4490	27.77
3	138	4680	28.77
Mean	137	4730	27.70
Std. Dev.	9	260	1.86
Coeff. of Variation	6.6%	5.5%	6.7%

TABLE 19
UNIDIRECTIONAL
TRANSVERSE TENSILE PROPERTIES
$(0°)_{15}$ @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	8.2	3630	2.55	0.02	Strain Gage
2	7.4	3380	2.58	-	Extensometer
3	6.8	3040	2.67	-	"
4	6.0	2640	2.83	-	"
5	7.0	3240	2.61	-	"
Mean	7.1	3190	2.65	0.02	
Std. Dev.	0.8	370	0.11	-	
Coeff. of Variation	11.3%	11.6%	4.2%	-	

PRESTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	POISSON'S RATIO	INSTRUMENTATION
1	6.8	3330	2.18	0.04	Strain Gage
2	6.9	3160	2.54	-	Extensometer
3	7.1	3480	2.44	-	"
4	7.1	3300	2.57	-	"
5	7.1	3240	2.61	-	"
Mean	7.0	3300	2.47	0.04	
Std. Dev.	0.1	120	0.17	-	
Coeff. of Variation	1.4%	3.6%	6.9%	-	

TABLE 20
ANGLEPLY
RAIL SHEAR PROPERTIES
$[0°/\pm45°/90°]_{2s}$ - 16-PLY @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

UNSTRESSED

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	27.0	11,380	3.49
2	24.3	10,990	3.32
3	23.6	12,870	3.49
Mean	25.0	11,750	3.43
Std. Dev.	1.8	990	0.10
Coeff. of Variation	7.2%	8.4%	2.9%

PRESTRESSED

SPECIMEN	ULT. STR., KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6
1	31.3	13,450	3.67
2	29.3	12,600	3.26
3	27.6	14,270	3.66
Mean	29.4	13,400	3.53
Std. Dev.	1.8	840	0.23
Coeff. of Variation	6.1%	6.3%	6.5%

E. DESIGN ALLOWABLE TESTING OF "NON-SPECIFICATION" GRADE TUNGSTEN SUBSTRATE BORON

The three batches of "non-specification" grade boron fiber used in this program were produced by Avco Corporation by operating their production line at higher rates of speed. Avco processed the three batches of "non-specification" boron fiber into 3-inch wide prepreg tape using 104 fiberglass scrim cloth and Narmco 2387 resin. However, at the higher production rate, fiber can be produced at a significantly lower cost, and it was theorized that prestressing should upgrade the properties of "non-specification" boron to the level of "specification" boron. Production of fiber at high speeds should lower the average fiber strength and increase the proportion of low strength fibers in the gaussian distribution of fiber strengths by increasing the average number of flaws per unit strength of fiber. The cost savings could be passed on to the industry. The objective of this phase of the program could not be met.

In order to upgrade the low strength "non-specification" fiber by prestressing, the fiber should have strength in the range of 360-420 ksi with a coefficient of variation over 25%. The first two batches had fiber properties nearly equal to "specification" grade boron. The third batch had very low fiber strength and could not be improved by prestressing. There were apparently too many flaws per unit length of fiber for prestressing to be effective.

To verify the high fiber strength of Batch 2, receiving inspection tests were run on the material. The longitudinal flexural strength values were as high as the values obtained on "specification" grade prepreg.

Longitudinal Flexural Str., ksi (R.T.)	275
Longitudinal Flexural Mod., msi (R.T.)	28.6
Short Beam Shear Str., ksi (R.T.)	14.7

Prestressing experiments were conducted on both Batches 2 and 3. The fiber strengths of the three batches are presented in Table 21. For comparison, the fiber strength of a typical batch of "specification" grade prepreg is presented in Table 22. There was some improvement in fiber strength properties but no improvement in composite longitudinal tensile strength. All work with "non-specification" grade material was discontinued. Experimental results are summarized in Tables 23 and 24.

TABLE 21

FIBER STRENGTH PROPERTIES OF "NON-SPECIFICATION" GRADE TUNGSTEN SUBSTRATE BORON/EPOXY PREPREG

UNSTRESSED BATCH NO.	AVG. FIBER STR., KSI (100 TESTS)	COEFF. OF VARIATION, %
1	463	22.3
	468	18.6
2	473	24.1
	473	21.4
	485	18.6
	481	23.3
	461	24.8
3	355	36.7

TABLE 22

FIBER STRENGTH PROPERTIES OF "SPECIFICATION" GRADE TUNGSTEN SUBSTRATE BORON/EPOXY PREPREG

UNSTRESSED ROLL NO.	AVG. FIBER STR., KSI (100 TESTS)	COEFF. OF VARIATION, %
R-190	494	19.2
R-191	480	21.8
R-192	486	19.3
R-193	472	22.8
R-194	504	14.6

TABLE 23
EFFECT OF PRESTRESSING ON FIBER PROPERTIES -
"NON-SPECIFICATION" GRADE BORON/EPOXY

BATCH 2			BATCH 3		
Roller Size (Inch) (40-lb. Load)	Avg. Fiber Str.,ksi	Coeff. of Var., %	Roller Size (Inch) (40-lb. Load)	Avg. Fiber Str.,ksi	Coeff. of Var., %
Unstressed	473	25.0	Unstressed	355	36.7
0.450	495	13.1	0.312	413	21.7
0.500	497	14.2	0.375	386	-
0.550	513	12.7	0.425	406	28.0
0.575	483	13.7	0.450	400	30.5
			0.475	402	24.8
			0.550	390	29.3
			0.600	366	29.2

TABLE 24
EFFECT OF PRESTRESSING ON COMPOSITE
LONGITUDINAL TENSILE STRENGTH -
"NON-SPECIFICATION" GRADE BORON/EPOXY

BATCH 2			BATCH 3		
Roller Size (Inch) (40-lb. Load)	Avg. Tensile Str., ksi (5 Specimens)	Coeff. of Var., %	Roller Size (Inch)	Avg. Tensile Str., ksi (5 Specimens)	Coeff. of Var., %
Unstressed	219	4.2	Unstressed	127	2.8
0.550	217	3.7	0.312	116	7.8
0.575	222	2.5	0.375	136	6.6
			0.425	130	
			0.450	130	-
			0.475	130	4.9
			0.525	138	3.6
			0.600	133	5.0

F. ANALYSIS OF DATA

Analysis of Static Test Data

A qualitative summary of the effect of prestressing is presented in Table 25. A comparison of the means for all tests comparing unstressed versus prestressed values is presented in Tables 26 through 33. In this comparison, the unstressed and prestressed tensile properties were analyzed statistically to determine if the differences in the means are significant. Statistical "t" tests on the means were run at the 95% probability level. To interpret these tables, note that the "t" value must be greater than the probability value if the difference between the means is significant.

A summarization of the effect of prestressing on the coefficient of variation of the test data is presented in Table 34. There is no indication in the data showing that prestressing decreases the coefficient of variation for "Rigidite" 5505/4. However, in the carbon substrate boron data, 11 out of 18 groups of data show a decrease in coefficient of variation.

A comparison of the unstressed and prestressed tensile strength of the $[0°/\pm45°/90°]_s$ 8-ply laminate orientation is important in analyzing the effect of prestressing. There is no evidence that prestressing increases or degrades angleply tensile properties for the materials used. Other tests on this angle orientation were run in addition to those reported in the design allowable testing program. Results of these tests are presented in Tables 35 through 38.

To further test the effect of prestressing, a lot of "Rigidite" 5505/4 was processed to give 25 coupons unstressed and 20 coupons prestressed. The longitudinal strength test results on these angleply coupons at room temperature were as follows:

	Ultimate	Coeff. of Variation
Unstressed - Avg. of 25	59.2 ksi	3.8%
Stressed - Avg. of 20	60.0 ksi	4.7%

TABLE 25

EFFECT OF PRESTRESSING ON MECHANICAL STRENGTH PROPERTIES

MECHANICAL STRENGTH PROPERTY	TEST TEMP.	EFFECT OF PRESTRESSING "SPECIFICATION" GRADE BORON/EPOXY	EFFECT OF PRESTRESSING CARBON CORE BORON/EPOXY
$[0/\pm 45/90]_8$ Tensile Strength	R.T.	No Change	No Change
$[0/\pm 45/90]_8$ Tensile Strain to Failure	R.T.	No Change	No Change
$[0/\pm 45/90]_8$ Tensile Modulus	R.T.	Increase	No Change
$[0/\pm 45/90]_8$ Tensile Strength	350F	No Change	No Change
$[0/\pm 45/90]_8$ Tensile Strain to Failure	350F	No Change	No Change
$[0/\pm 45/90]_8$ Tensile Modulus	350F	Increase	No Change
$[0]_8$ Longitudinal Tensile Strength	R.T.	Decrease	Increase
$[0]_8$ Longitudinal Tensile Strain to Failure	R.T.	Decrease	Increase
$[0]_8$ Longitudinal Tensile Modulus	R.T.	No Change	No Change
$[0]_8$ Longitudinal Tensile Strength	350F	Decrease	Increase
$[0]_8$ Longitudinal Tensile Strain to Failure	350F	No Change	No Change
$[0]_8$ Longitudinal Tensile Modulus	350F	No Change	Increase
$[0]_8$ Longitudinal Compression Strength	R.T.	No Change	No Change

TABLE 25

EFFECT OF PRESTRESSING ON MECHANICAL STRENGTH PROPERTIES (Continued)

MECHANICAL STRENGTH PROPERTY	TEST TEMP.	EFFECT OF PRESTRESSING "SPECIFICATION" GRADE BORON/EPOXY	EFFECT OF PRESTRESSING CARBON CORE BORON/EPOXY
$[0]_8$ Longitudinal Compression Strain to Failure	R.T.	No Change	No Change
$[0]_8$ Longitudinal Compression Modulus	R.T.	No Change	No Change
$[0]_8$ Longitudinal Compression Strength	350F	No Change	No Change
$[0]_8$ Longitudinal Compression Strain to Failure	350F	No Change	No Change
$[0]_8$ Longitudinal Compression Modulus	350F	No Change	No Change
$[0]_{15}$ Transverse Tensile Strength	R.T.	Increase	No Change
$[0]_{15}$ Transverse Tensile Strain to Failure	R.T.	Increase	No Change
$[0]_{15}$ Transverse Tensile Modulus	R.T.	No Change	No Change
$[0/\pm45/90]_{16}$ Rail Shear Strength	R.T.	No Change	Increase
$[0/\pm45/90]_{16}$ Rail Shear Strain to Failure	R.T.	No Change	No Change
$[0/\pm45/90]_{16}$ Rail Shear Modulus	R.T.	No Change	No Change

TABLE 26
COMPARISON OF MEANS
ANGLEPLY LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	65.2	7040	10.73
Prestressed (mean)	61.8	6530	11.28
"t" Value	1.42	1.43	4.17
Probability Value*	2.23	2.23	2.23
Diff.Between Means	Not Significant	Not Significant	Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	56.8	7350	9.09
Prestressed (mean)	52.7	6480	9.07
"t" Value	1.82	1.93	0.06
Probability Value*	2.23	2.23	2.23
Diff.Between Means	Not Significant	Not Significant	Not Significant

*Taken from: Applied Statistics for Engineers by William Volk, McGraw-Hill Book Company, 1969, New York, New York, page 111.

TABLE 27
COMPARISON OF MEANS
ANGLEPLY LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ @ 350F

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	57.4	7930	8.33
Prestressed (mean)	58.3	6820	9.71
"T" Value	0.25	1.91	4.35
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	51.5	6260	8.85
Prestressed (mean)	50.8	6520	8.55
"T" Value	0.25	0.53	1.13
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

* See Table 26.

TABLE 28
COMPARISON OF MEANS
UNIDIRECTIONAL LONGITUDINAL
TENSILE PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	221	7590	30.54
Prestressed (mean)	210	7080	30.75
"t" Value	2.58	2.74	0.38
Probability Value*	2.10	2.10	2.10
Diff.Between Means	Significant	Significant	Not Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	165	6440	27.52
Prestressed (mean)	186	7420	26.97
"t" Value	4.88	7.41	0.96
Probability Value*	2.10	2.10	2.10
Diff.Between Means	Significant	Significant	Not Significant

*See Table 26.

TABLE 29
COMPARISON OF MEANS
UNIDIRECTIONAL LONGITUDINAL
TENSILE PROPERTIES
$(0°)_8$ @ 350F

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	200	7300	28.26
Prestressed (mean)	171	5980	29.71
"T" Value	4.77	2.21	0.94
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Significant	Not Significant	Not Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	125	6060	25.85
Prestressed (mean)	155	5840	28.34
"T" Value	3.64	0.35	1.32
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Significant	Not Significant	Not Significant

* See Table 26.

TABLE 30
COMPARISON OF MEANS
UNIDIRECTIONAL LONGITUDINAL
COMPRESSION PROPERTIES
$(0°)_8$ @ ROOM TEMPERATURE

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	284	8700	32.22
Prestressed (mean)	288	8630	32.96
"T" Value	0.79	0.36	1.75
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	264	9540	28.00
Prestressed (mean)	274	9700	27.92
"T" Value	0.87	0.30	0.28
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

* See Table 26.

TABLE 31
COMPARISON OF MEANS
UNIDIRECTIONAL LONGITUDINAL
COMPRESSION PROPERTIES
$(0°)_8$ @ 350F

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	139	4060	32.87
Prestressed (mean)	133	3840	34.07
"T" Value	1.02	0.88	1.24
Probability Value*	2.31	2.36	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	147	4980	29.14
Prestressed (mean)	137	4730	27.70
"T" Value	0.94	0.73	1.28
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

* See Table 26.

TABLE 32
COMPARISON OF MEANS
UNIDIRECTIONAL TRANSVERSE
TENSILE PROPERTIES
$(0°)_{15}$ @ ROOM TEMPERATURE

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	7.6	3180	2.75
Prestressed (mean	8.5	3640	2.75
"T" Value	3.74	2.85	0
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Significant	Significant	None

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	7.1	3190	2.65
Prestressed (mean)	7.0	3300	2.47
"T" Value	0.28	0.63	1.99
Probability Value*	2.31	2.31	2.31
Diff. Between Means	Not Significant	Not Significant	Not Significant

* See Table 26.

TABLE 33
COMPARISON OF MEANS
ANGLEPLY RAIL SHEAR PROPERTIES
$[0°/\pm45°/90°]_s$ - 16-PLY @ ROOM TEMPERATURE

"SPECIFICATION" GRADE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	26.3	12,770	4.91
Prestressed (mean)	29.5	12,410	4.25
"T" Value	0.71	0.82	1.04
Probability Value*	2.78	2.78	2.78
Diff. Between Means	Not Significant	Not Significant	Not Significant

CARBON CORE BORON	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	25.0	11,750	3.43
Prestressed (mean)	29.4	13,400	3.53
"T" Value	2.99	2.20	0.69
Probability Value*	2.78	2.78	2.78
Diff. Between Means	Significant	Not Significant	Not Significant

* See Table 26.

TABLE 34

INFLUENCE OF PRESTRESSING ON COEFFICATION OF VARIATION

LAMINATE ORIENTATION	MECH. STR. PROPERTY	TEST TEMP.	"SPECIFICATION" GRADE BORON RIGIDITE 5505/4		CARBON SUBSTRATE BORON	
			UNSTRESSED	PRESTRESSED	UNSTRESSED	PRESTRESSED
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Strength	R.T.	3.1	8.1	6.7	7.6
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Strain to Failure	R.T.	5.1	11.2	10.6	12.0
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Modulus	R.T.	4.7	3.6	8.5	0.7
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Strength	350F	2.8	13.4	11.3	3.9
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Strain to Failure	350F	5.7	17.9	15.2	7.8
$[0°/\pm45°/90°]_s$	Longitudinal Tensile Modulus	350F	6.5	4.7	3.6	5.8
$[0°]_8$	Longitudinal Tensile Strength	R.T.	4.1	4.8	4.8	5.9
$[0°]_8$	Longitudinal Tensile Strain to Failure	R.T.	5.4	5.9	3.9	4.6
$[0°]_8$	Longitudinal Tensile Modulus	R.T.	3.0	4.8	5.4	3.8

TABLE 34
INFLUENCE OF PRESTRESSING ON COEFFICATION OF VARIANCE (Continued)

LAMINATE ORIENTATION	MECH.STR. PROPERTY	TEST TEMP.	"SPECIFICATION" GRADE BORON RIGIDITE 5505/4		CARBON SUBSTRATE BORON	
			UNSTRESSED	PRESTRESSED	UNSTRESSED	PRESTRESSED
$[0°]_8$	Longitudinal Tensile Strength	350F	4.0	6.4	11.2	7.7
$[0°]_8$	Longitudinal Ten-Strain to Failure	350F	6.7	20.7	18.8	14.2
$[0°]_8$	Longitudinal Tensile Modulus	350F	7.2	9.4	11.7	8.9
$[0°]_{15}$	Transverse Tensile Strength	R.T.	6.6	2.4	11.3	1.4
$[0°]_{15}$	Transverse Tensile Strain to Failure	R.T.	9.4	5.5	11.6	4.2
$[0°]_{15}$	Transverse Tensile Modulus	R.T.	1.1	2.2	3.6	6.9
$[0°]_8$	Longitudinal Compression Strength	R.T.	2.8	2.8	6.1	7.3
$[0°]_8$	Longitudinal Compression Strain to Failure	R.T.	2.8	3.9	9.4	7.8
$[0°]_8$	Longitudinal Compression Modulus	R.T.	1.9	2.2	1.7	1.5

TABLE 34
INFLUENCE OF PRESTRESSING ON COEFFICATION OF VARIATION (Concluded)

LAMINATE ORIENTATION	MECH.STR. PROPERTY	TEST TEMP.	"SPECIFICATION" GRADE BORON RIGIDITE 5505/4		CARBON SUBSTRATE BORON	
			UNSTRESSED	PRESTRESSED	UNSTRESSED	PRESTRESSED
$[0°]_8$	Longitudinal Compression Strength	350F	1.4	7.5	10.9	6.6
$[0°]_8$	Longitudinal Compression Strain to Failure	350F	3.6	8.3	10.6	5.5
$[0°]_8$	Longitudinal Compression Modulus	350F	2.8	4.0	2.0	6.7
$[0°/\pm45°/90°]_{2s}$	Rail Shear Strength	R.T.	10.6	24.7	7.2	6.1
$[0°/\pm45°/90°]_{2s}$	Rail Shear Strain to Failure	R.T.	3.9	4.6	8.4	6.3
$[0°/\pm45°/90°]_{2s}$	Rail Shear Modulus	R.T.	21.8	6.1	2.9	6.5

TABLE 35
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm 45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
RIGIDITE 5505/4

UNSTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	INSTRUMENTATION
1	61.7	6720	11.43	Extensometer
2	61.0	6420	11.31	"
3	61.2	6840	11.43	"
4	59.0	6480	11.04	"
5	64.5	7380	11.04	"
Mean	61.5	6770	11.25	
Std. Dev.	2.0	380	0.20	
Coeff. of Variation	3.2%	5.7%	1.8%	

PRESTRESSED

SPECIMEN NO.	ULT. STR. KSI	STRAIN TO FAILURE, MICROINCHES	MODULUS PSI x 10^6	INSTRUMENTATION
1	48.9*	5120*	11.04*	Extensometer
2	62.7	7140	10.47	"
3	63.4	7120	11.27	"
4	64.3	7320	11.39	"
5	64.0	7180	11.39	"
Mean	63.6	7190	11.11	
Std. Dev.	0.7	90	0.39	
Coeff. of Variation	1.1%	1.2%	3.5%	

* Specimen failed in grips - not included in mean

TABLE 36
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

SPECIMEN NO.	UNSTRESSED ULT. STR., KSI	PRESTRESSED ULT. STR., KSI
1	49.3	51.8
2	52.2	49.8
3	50.0	48.3
4	50.5	51.0
5	50.0	48.0
6	50.0	49.8
7	49.3	49.5
8	46.9	50.0
9	49.3	54.1
10	44.6	50.9
11	42.2	50.5
12	50.7	49.8
13	48.6	50.2
14	52.2	52.4
15	50.5	50.9
16	45.5	51.0
17	49.0	50.2
18	52.4	48.8
19	51.4	46.6
20	46.1	50.0
Mean	49.0	50.2
Std. Deviation	2.7	1.6
Coeff. of Variation	5.5%	3.2%

TABLE 37
COMPARISON OF MEANS
ANALYSIS OF DATA IN TABLE 35
ANGLEPLY LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
"RIGIDITE"5505/4

	ULT.STR. KSI	STRAIN MICROINCHES	MODULUS PSI X 10^6
Unstressed (mean)	61.5	6770	11.25
Prestressed (mean)	63.6	7190	11.11
"T" Value	2.22	2.13	0.71
Probability Value*	2.36	2.36	2.36
Diff. Between Mean	Not Significant	Not Significant	Not Significant

* See Table 26.

TABLE 38
COMPARISON OF MEANS
ANALYSIS OF DATA IN TABLE 37
ANGLEPLY LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

Ultimate Tensile Strength Unstressed (mean)	49.0
Ultimate Tensile Strength Prestressed (mean)	50.2
"T" Value	1.71
Probability Value*	2.02
Diff. Between Means	Not Significant

* See Table 26.

An angleply laminate made from prestressed carbon substrate boron had a longitudinal tensile strength of approximately 60 ksi. The laminate was cured with more bleeder plies (3 plies 112 and 1 ply 181 versus 3 plies 112) to maximize fiber volume. Fiber volume was 51% which was somewhat higher than the 47-49% fiber volume which was obtained using 3 plies 112 bleeder. Data is presented in Table 39.

TABLE 39
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
CARBON SUBSTRATE BORON

PRESTRESSED

SPECIMEN NO.	ULT. STRENGTH, KSI
1	62.1
2	57.8
3	61.0
4	63.7
5	57.9
6	59.1
7	62.1
8	62.1
9	55.2
10	62.4
11	60.0
12	61.9
13	62.0
14	59.1
Mean	60.4
Std. Deviation	2.4
Coeff. of Variation	4.0%

Analysis of Fatigue Test Data

Fatigue tests were run at a stress ratio of 0.1 and a frequency of 1800 cycles per second. Further details on the test are given in the Appendix. Results are tabulated in Tables 40 and 41. "Specification" grade boron was significantly improved in fatigue by prestressing. Fatigue life of carbon substrate boron was reduced at high stress levels but not at low stress levels.

TABLE 40
UNIDIRECTIONAL
TENSION-TENSION FATIGUE TEST RESULTS
$(0°)_8$ @ ROOM TEMPERATURE - R=0.1
"RIGIDITE" 5505/4

NOMINAL LOAD, KSI	UNSTRESSED SPECIMENS CYCLES TO FAILURE	PRESTRESSED SPECIMENS CYCLES TO FAILURE
110	7,414,000 (No Failure)	
115	-	5,628,000 (No Failure)
120	-	5,479,000 (No Failure)
125	-	7,425,000 (No Failure)
130	2,642,000 (No Failure	5,250,000 (No Failure)
135	2,745,000	5,016,000 (No Failure)
140	1,400,000	10,318,000 (No Failure)
145	183,000	3,766,000 (No Failure)
150	114,000	2,556,000 (No Failure)
155	206,000	1,071,000
160	30,000	555,000
165	25,500	1,758,000
170	17,000	35,000
175	15,000	49,000
180	9,000	-
185	2,000	63,000

TABLE 41
UNIDIRECTIONAL
TENSION-TENSION FATIGUE TEST RESULTS
$(0°)_8$ @ ROOM TEMPERATURE - R=0.1
CARBON SUBSTRATE BORON

NOMINAL LOAD, KSI	UNSTRESSED SPECIMENS CYCLES TO FAILURE	PRESTRESSED SPECIMENS CYCLES TO FAILURE
90	6,692,000	6,977,000 (No Failure)
95	-	5,111,000 (No Failure)
100	9,819,000	6,278,000 (No Failure)
100	10,115,000	5,637,000 (No Failure)
110	2,480,000	5,127,000 (No Failure)
110	-	4,034,000 (No Failure)
112.5	-	166,000
115	2,551,000	109,000
115	-	-
120	745,000	20,000
125	79,000	34,000
130	170,000	7,000
130	40,000	4,000
140	11,000	2,000
145	9,000	200
145	-	100

Calculation of B-Allowables

B-allowables were calculated from the prestressed and unstressed test results shown in the previous tables, and the allowables are tabulated in Table 42. Calculations were made using the equation:

B-allowable = mean value – K(standard deviation)

where K, the tolerance limit factor, was taken from Table 9.6.4.1, Military Standardization Handbook MIL-HDBK-5B, 1 Sept. 1971.

"B"-allowables are higher for the prestressed carbon core boron and somewhat lower for the "specification" grade boron, "Rigidite" 5505/4.

TABLE 42
"B" ALLOWABLES* CALCULATED FOR
UNSTRESSED AND PRESTRESSED BORON LAMINATES

MECHANICAL PROPERTY	TEST TEMP.	"SPECIFICATION" GRADE		CARBON SUBSTRATE BORON	
		UNSTRESSED	PRESTRESSED	UNSTRESSED	PRESTRESSED
0° Tensile Strength	R.T.	199	187	146	160
0° Tensile Strain	R.T.	6620	6090	5850	6630
0° Tensile Strength	350F	173	134	77	114
0° Tensile Strain	350F	5630	1760	2180	3010
Angleply Tensile Strength	R.T.	58.4	48.0	45.4	40.7
Angleply Tensile Strain	R.T.	5810	4040	4690	3820
Angleply Tensile Strength	350F	52.0	31.7	31.7	44.0
Angleply Tensile Strain	350F	6400	2660	-	4780
0° Compression Strength	R.T.	257	261	210	206
0° Compression Strain	R.T.	7880	-	6470	7110
90° Tensile Strength	R.T.	5.9	7.8	4.4	6.7
90° Tensile Strain	R.T.	2160	2960	1930	2890

* Tolerance limit factors taken from Military Standardization Handbook MIL-HDBK-5B, 1 Sept. 1971.

"B"-allowables calculated for the angleply composite data shown in Table 35 are as follows:

	Unstressed	Prestressed
Tensile Strength	54.7	60.7
Tensile Strain	5480	6820

G. ANALYSIS OF THE ECONOMIC IMPACT OF PRESTRESSING ON TAPE PRODUCTION

Boron fiber is manufactured in a vapor deposition process. Continuous tungsten substrate wires are drawn through a reactor containing boron trichloride (BCl_3) and hydrogen gases. The tungsten wire is heated resistively to about 1300C as it passes through the reactor at a rate of 15 ft/min. At this temperature, hydrogen reduces the boron trichloride depositing boron. Many types of flaws can be formed during the boron deposition process. Figure 4 shows a typical flaw at the site of fiber fracture. Such flaws are present in all fibers; however, their occurrence in high-strength fiber (525-550 ksi average fiber strength on three-inch gage length) is minimal. Careful control of wire temperature, gas flow rate, etc., is required to minimize the number of flaws.

A significant cost savings could be realized if a fiber was produced containing more flaws per unit length which would be subsequently prestressed to eliminate the effect of the additional flaws. Cost savings could be realized in four areas:

1. A higher production rate could be realized.
2. Fewer production personnel would be required.
3. More efficient recovery of boron trichloride gas would be possible.
4. Less expensive capitol equipment, particularly less expensive electrical control units and gas control flow units could be used.

Flaws, Their Genesis, and Their Relation to Lower Cost Boron

Two types of flaws which are most prevalent, but which are eliminated to as great an extent as possible by close process monitoring, are discussed below in order to present their relation to prestressing, tape quality, and production costs.

1. Crystal Flaw. One of the most common defects in boron filament is the crystal flaw. Figure 5 gives a side view and an end view of a crystal flaw in a boron fiber. Fibers containing crystal flaws have tensile strengths of 100-400 ksi, depending upon the size and location of the crystal in the fiber. Figure 5 also shows schematically the locations in the reactor where

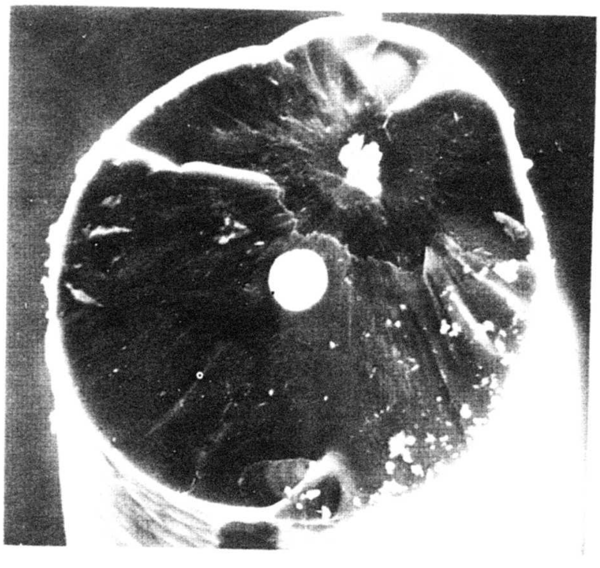


FIGURE 4. DEFECT SITE ON BORON FILAMENT FRACTURE

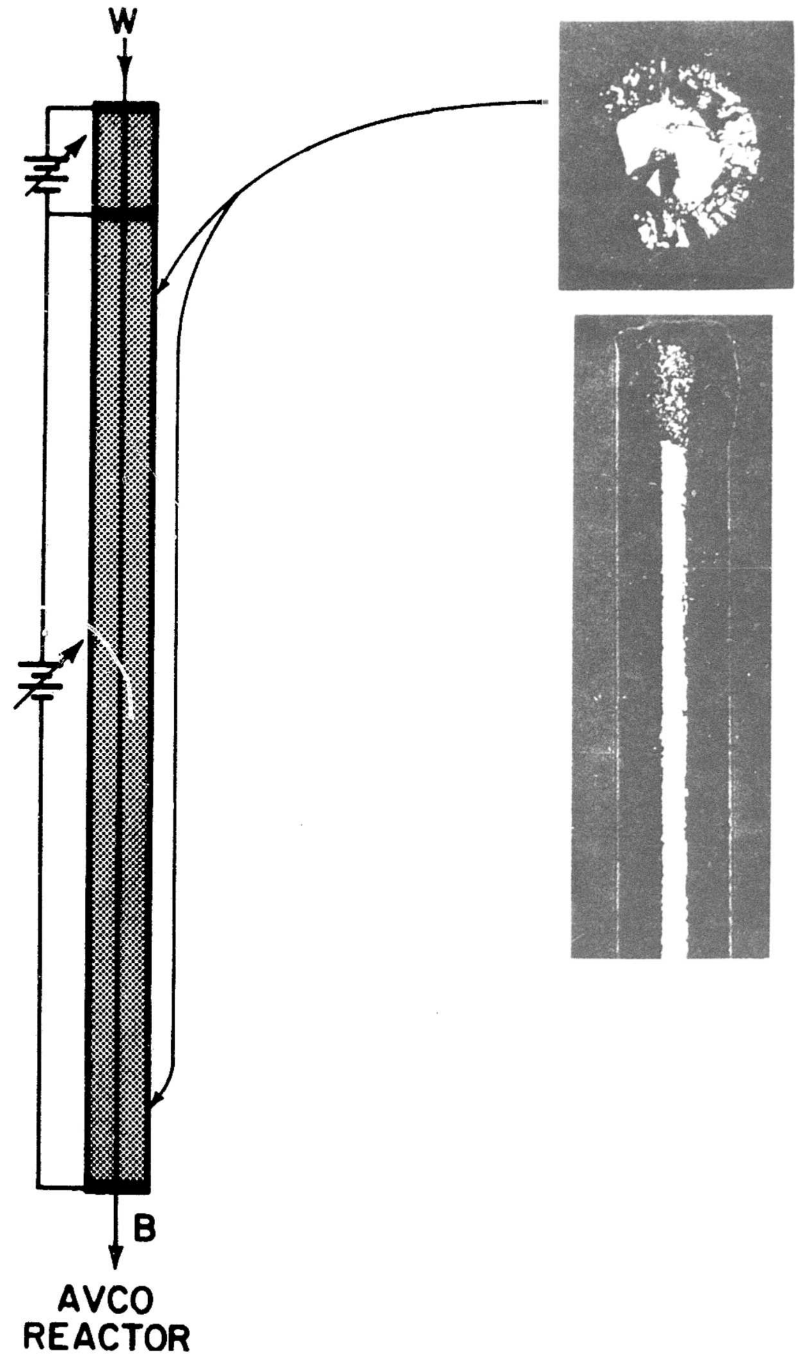


FIGURE 5. GENESIS OF CRYSTAL FLAW

crystals can be formed. Crystals occur if too high a hot spot temperature is reached, about 50C greater than 1300C. Figure 6 shows a schematic diagram of the temperature profile in a boron reactor. Crystals also form if too low a gas flow rate is used in the reactor because of kinetic and equilibrium effects which result as by-product species built up in the reactor.

The onset of crystal formation from increased temperature or decreased flow is not a catastrophic phenomenon, but instead is approached monotonically as operating parameters are varied. As "some" higher temperatures and as "some" lower gas flow is reached, crystals appear only intermittently every 1000 feet or 100 feet or 10 feet, and they appear only because superimposed upon steady state are normal fluctuations which carry the deposition into the crystal flaw induction range.

Typical production filament strength is given in the histogram, Figure 7. The monotonic occurrence of crystals has been well delineated in parameter studies and a typical histogram of filament exhibiting a crystal about every 10-20 feet is given in Figure 8 (and is superimposed on the production filament histogram for comparison). The filament whose tensile histogram is shown in Figure 8 was made with a hot spot temperature about 50C higher, and in a reactor operating about 1-1/2 fpm* faster than normal. Again, it will be noted from examination of Figure 8 that the onset of crystal formation is not catastrophic but, instead, arises gradually, i.e., the average tensile strength does not degrade 200 or 300 ksi, but instead the histogram is comprised of many "highs" and some "lows." If the reactor is operated still another 50C higher, substantially more severe crystal formation is evident, and Figure 9 gives a histogram of such filament; a surface photomicrograph of such material, also shown in Figure 9, indicates that the frequency of crystals is very high and, in fact, they are almost continuous along the filament.

* feet per minute

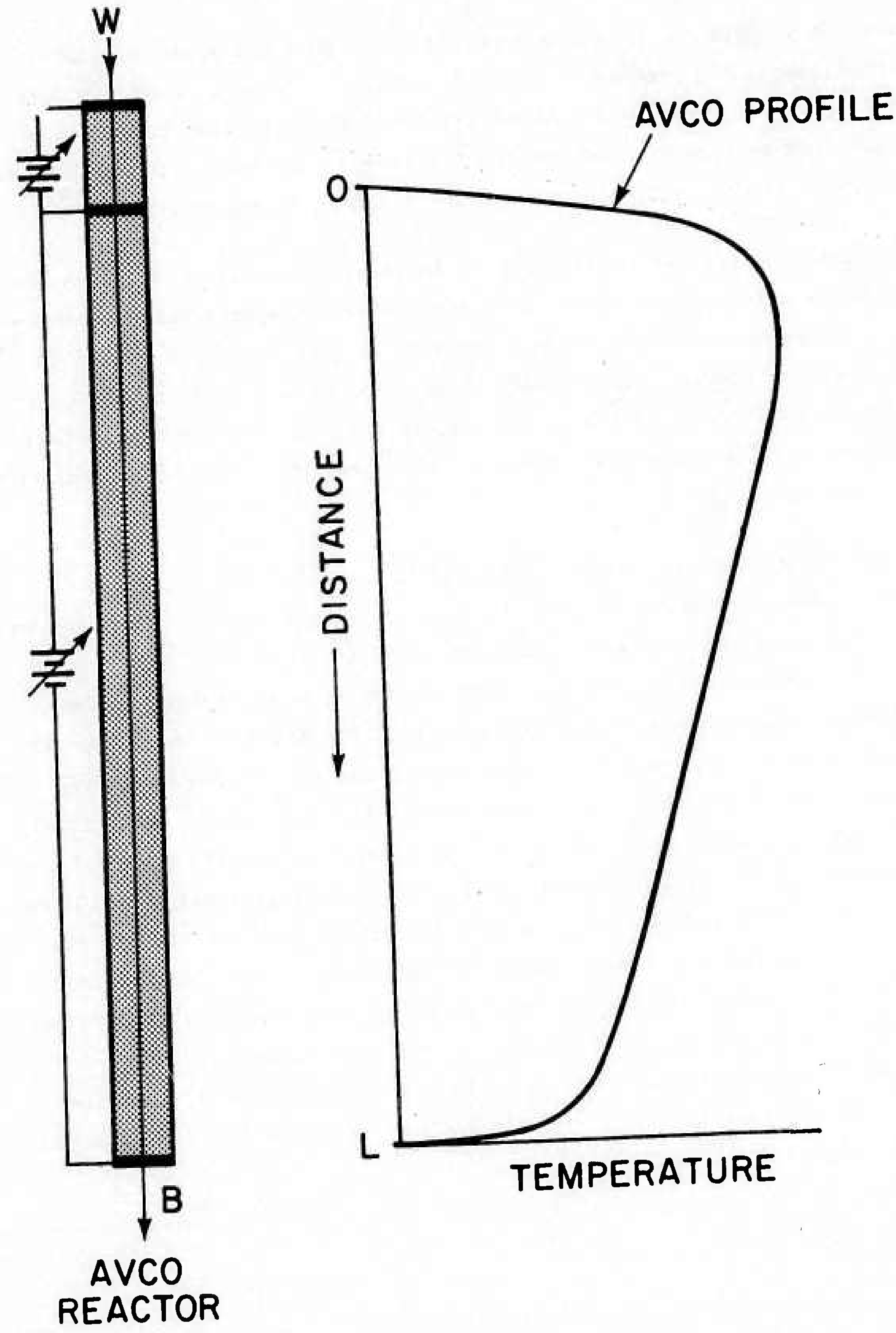


FIGURE 6. SCHEMATIC DIAGRAM OF BORON FILAMENT REACTOR AND TEMPERATURE PROFILE

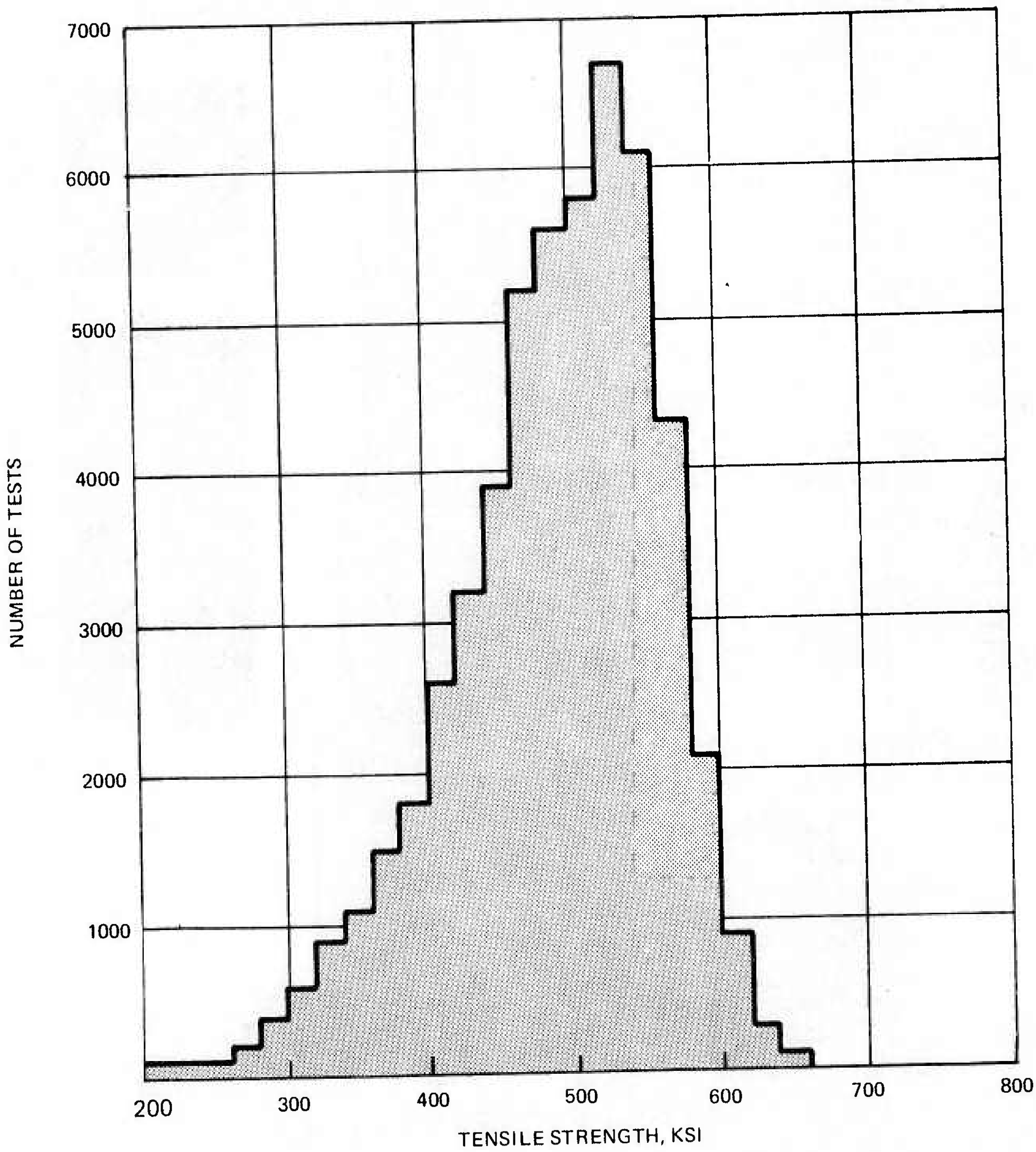


FIGURE 7. HISTOGRAM OF TYPICAL PRODUCTION FILAMENT

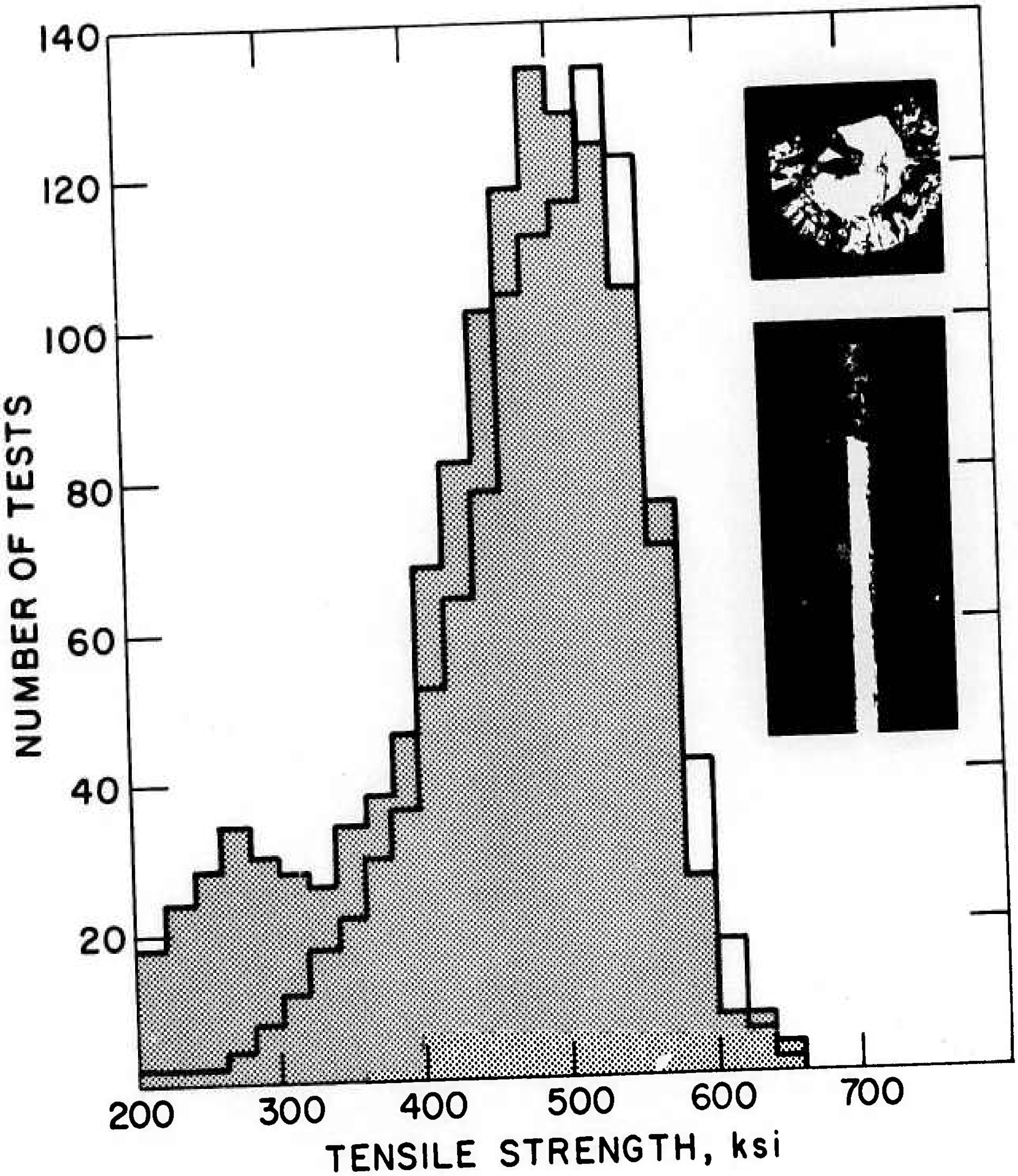


FIGURE 8. HISTOGRAM OF FILAMENT WITH LOW FREQUENCY OF CRYSTAL FLAWS

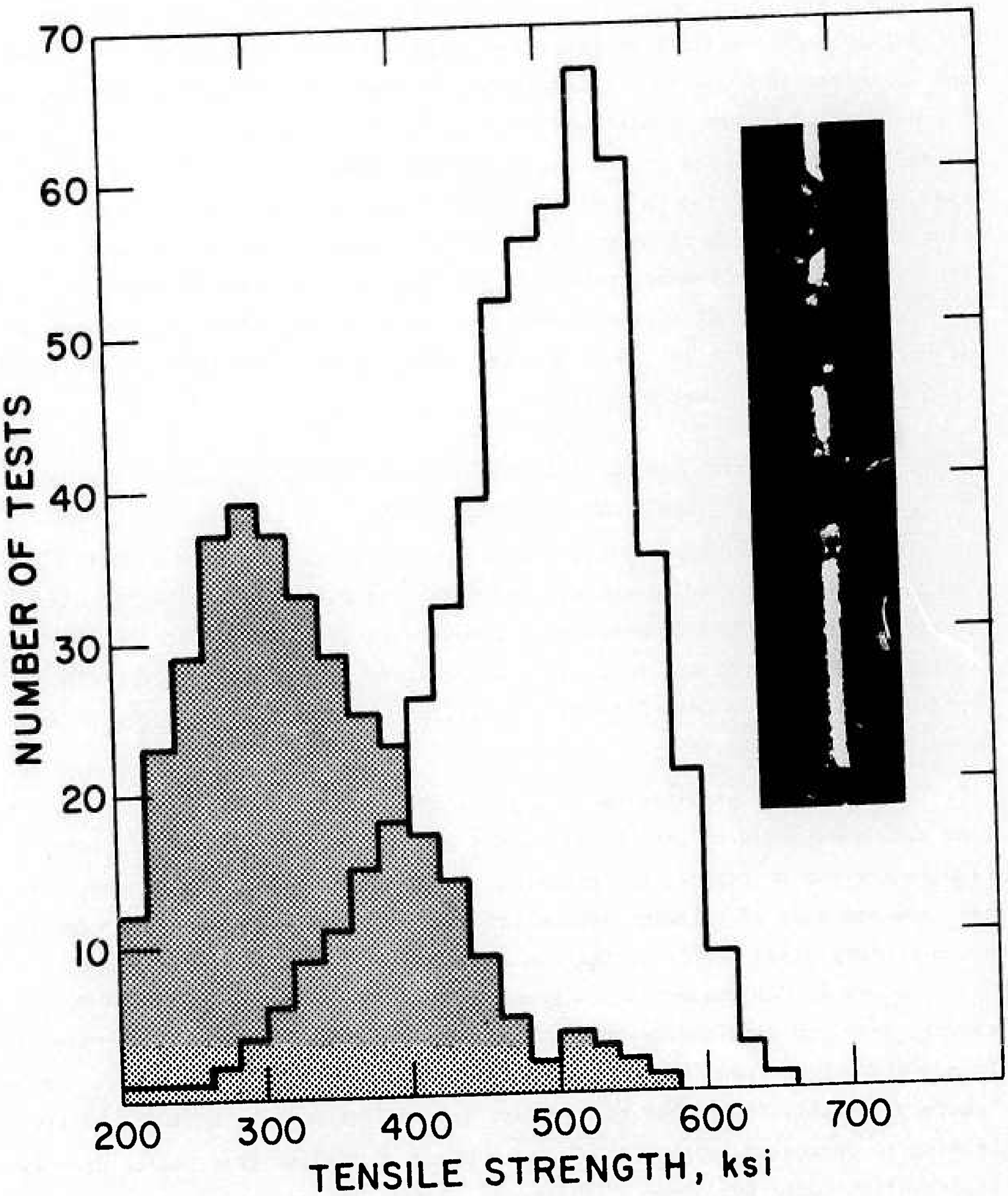


FIGURE 9. HISTOGRAM OF FILAMENT WITH HIGH FREQUENCY OF CRYSTAL FLAWS

2. Crack Tip Flaw. An end view of the crack tip flaw is shown in Figure 10. This defect has been related to variations in the filament temperature profile as a function of filament drawing rate. The crack tip flaw arises when the temperature at the larger diameter portion of the filament is increased above some critical level. This would happen if VHF heating is superimposed on the DC heating. VHF-augmentation has proven to be a viable processing technique for increasing production speed. A histogram of boron fiber produced at 30 fpm in a 6-foot long reactor and 10 SCFM total gas flow using VHF augmentation is shown in Figure 11. About 40% of the filaments test below 400 ksi, however, with the same high mode of over 500 ksi, as found in normal filament. At speeds higher than about 35 fpm substantially more of the filament is in the less than 400 ksi category and, in addition, substantial "splitting" of the filament is found.

Economic Aspects of the Crystal and Crack Tip Flaws When Considered in Conjunction with Prestressing of Boron/Epoxy Prepreg

VHF-augmentation can produce 4-mil boron filament at a rate a factor of 2 above solely dc heated reactors. The factor of 2 in drawing rate results directly in a factor of 2 decrease in labor costs to produce the filament. Decreases in BCl_3 recovery costs and, in addition, per pound decreases in depreciation costs of both filament production reactors and the recovery and recycle system result.

Equilibrium considerations of crystal formation limit the minimum gas flow rate that could be used during boron deposition. If the exit filament temperature can be raised, for example, via VHF-augmentation techniques, the gas flow per unit of filament production can be decreased because the equilibrium concentration of HCl (specifically delineated) can be increased, and the increase in HCl concentration translates directly to a decrease in BCl_3 recycle rate and simultaneously translates to a decrease in recovery losses. In addition, based upon the reduced gas rate per pound of filament, for a given recovery capacity the number of reactors can be increased by a factor of two, leading to decreased capital costs for a plant of a given size and to decreased depreciation costs per pound of filament. Similarly, operating the hot spot

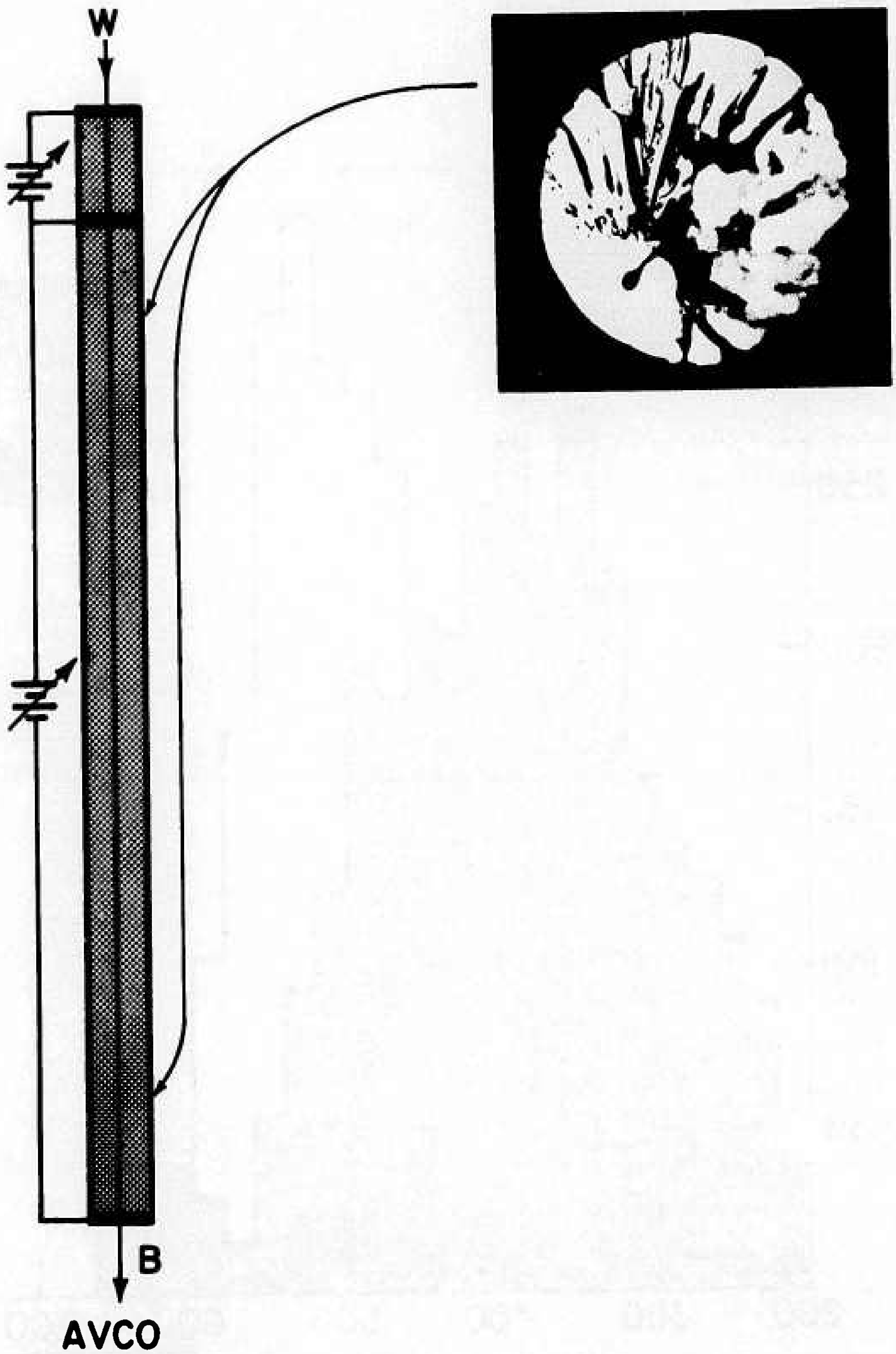


FIGURE 10. GENESIS OF THE CRACK TIP FLAW

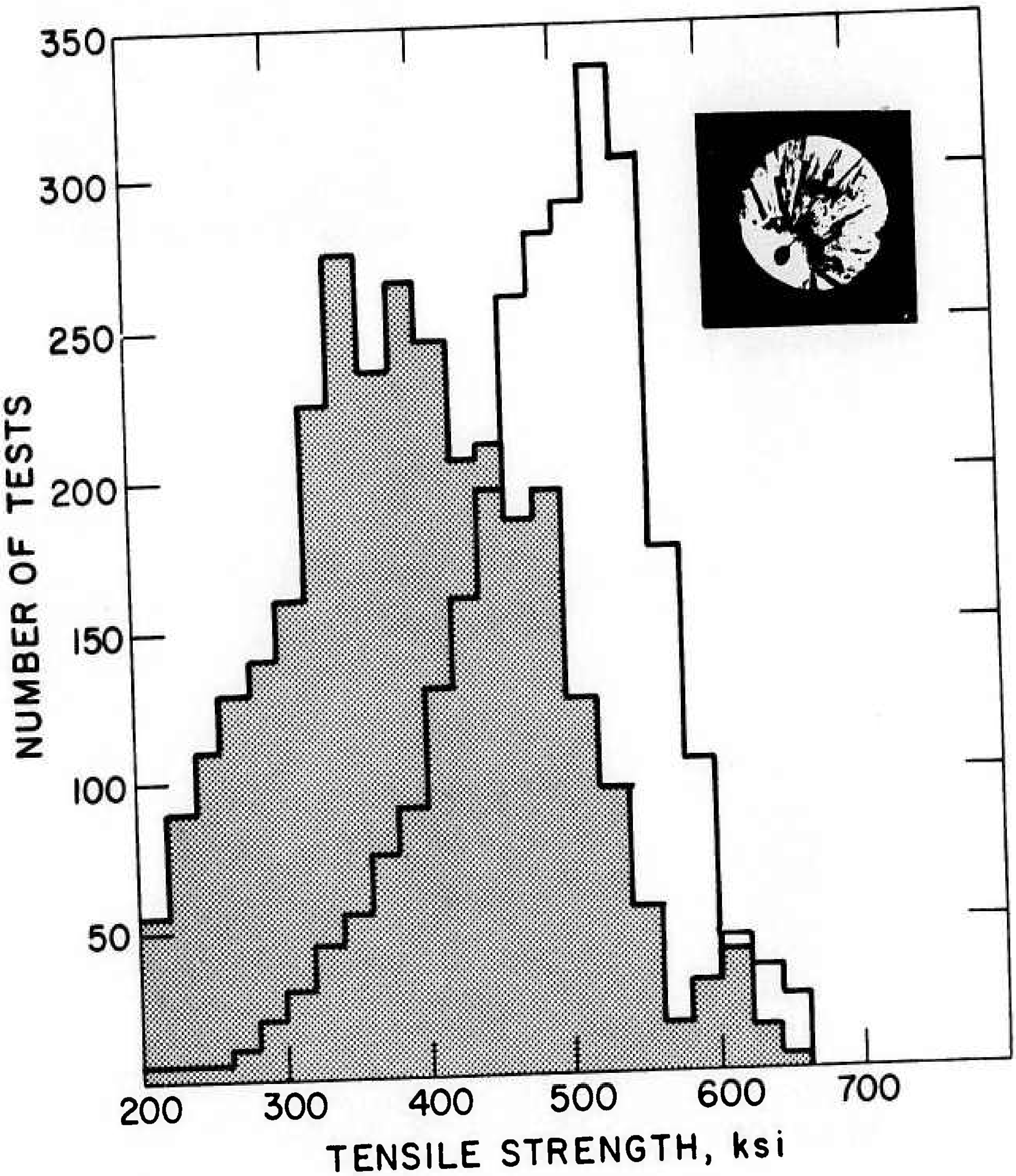


FIGURE 11. HISTOGRAM OF FILAMENT WITH CRACK TIP FLAW

temperature at about 50C higher than 1300C can add another 2 fpm speed increase to a total drawing rate of about 32 fpm. Both higher hot spot temperature and VHF-augmentation have been tested simultaneously at a total gas flow of 10 SLPM*.

Table 43 presents a current breakdown of the fixed and operating costs for "standard" 4-mil boron filament tape at a production level of 50,000 pounds/year. The potential costs for prestressed boron/epoxy tape based upon the reductions in labor, raw materials, and capital costs are also shown for comparison. A cost reduction of 23% based upon raw materials alone is an impetus to investigate the incorporation of controlled defect boron filament into boron/epoxy tape. The further decrease of 39% in production labor for an ultimate cost to the fabricator of $87/pound of prepreg can result in marked increases in the utilization of boron filament and, further, can make it cost competitive with graphite.

H. ANALYSIS OF LOW ANGLEPLY TENSILE PROPERTIES

Serious problems were encountered in the design allowable testing program in obtaining acceptable room temperature tensile properties for unstressed composites with the 0°/+45°/-45°/90°/90°/-45°/+45°/0° orientation. Acceptable room temperature longitudinal tensile properties for this orientation are:[3,4]

Tensile Strength, ksi	60 - 70
Strain to Failure, μin/in	6000
Modulus, psi x 10^6	9 - 11

Early in the program tensile properties were consistently low:

Tensile Strength, ksi	25 - 40
Strain to Failure, μin/in	3000 - 4000
Modulus, psi x 10^6	9 - 11

* Standard Liters Per Minute

(3) "Design Data for Composite Structure Safelife Prediction," E.C. Durchlamb et al, AFML-TR-73-225.

(4) Advanced Composites Design Guide.

TABLE 43
COMPARISON OF COSTS FOR "SPECIFICATION" GRADE
BORON PREPREG VS. CONTROLLED DEFECT BORON PREPREG

		CASE 1 "SPECIFICATION" GRADE BORON	CASE 2 CONTROLLED DEFECT BORON
Number of Reactors		600	600
Drawing Rate	FPM	15	30
Filament Production Rate	Lb/Year	50,000	100,000*
Tape Production Rate	Lb/Year	75,000	150,000
Materials	$/Lb Tape		
BCl_3		14	8
Substrate		31	24**
Other Chemicals, Resins		11	11
Direct Labor	$/Lb Tape	18	11
Indirect Costs (local taxes, depreciation, etc.)	$/Lb Tape	23	13***
G&A and Royalties	$/Lb Tape	11	7
Subtotal	$/Lb Tape	108	74
Profit (18% before taxes)		19	13
Selling Price	$/Lb Tape	127	87

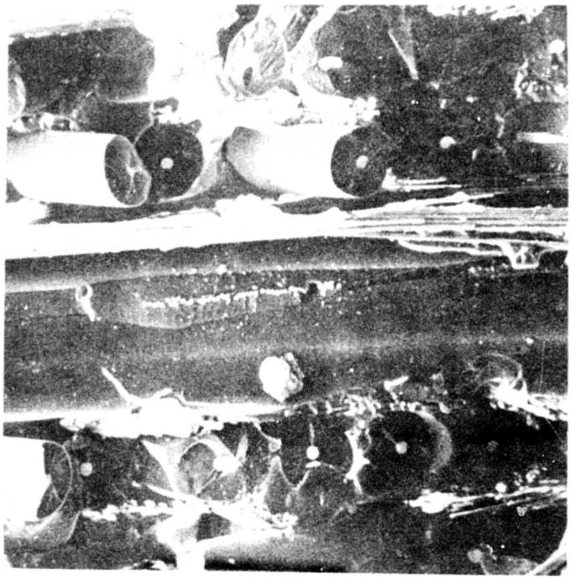
* With no increase in gas recovery capacity.
** Estimated.
*** No additional capital investment in gas recovery.

There was no obvious solution to the problem: (1) composite fabrication procedures, machining, and testing procedures common to the industry were being used; (2) all the prepreg that was used passed receiving inspection tests. Typical properties of unidirectional composites were high (longitudinal tension strength: 220 ksi, longitudinal flex. strength: 270 ksi, short beam shear strength: 15 ksi). Both fiber sensitive properties and resin sensitive properties were high. (3) Photomicrographic analyses showed no obvious difference between low and high strength coupons. In Figures 12 and 13, SEM analyses are shown of the fracture areas of a high strength specimen (74 ksi) and a low strength specimen (29 ksi). Both specimens show areas of good bonding and areas of fiber pull-out. In Figures 14, photomicrographs at 100X of the coupon cross-sectional areas are shown. It is difficult to make detailed analyses of boron/epoxy photomicrographs because the resin areas around the fibers crack so easily during polishing. However, it is obvious that gross voids and delaminations that could come from processing are not present in the low strength coupon.

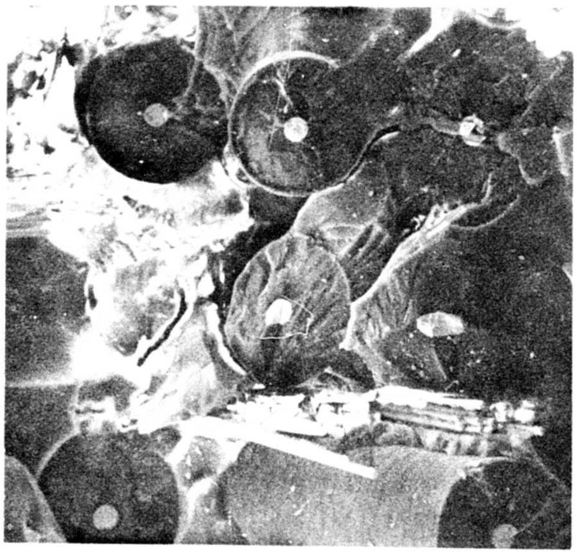
The nature of the problem can be seen in the tests run on Batch 57, a seven-pound lot of "Rigidite" 5505/4 prepreg. The receiving inspection tests were fully acceptable as shown in Table 44. However, the room temperature angleply longitudinal tensile strength was below 30 ksi. Tabulated angleply tensile strengths are shown in Table 45.

TABLE 44
RECEIVING INSPECTION TEST
BATCH 57 - "RIGIDITE"5505/4

MECHANICAL PROPERTY TEST	ULT. STR., KSI	SPEC. MINIMUM
Longitudinal Flexural Strength (Avg. of 3 coupons)	268	225
Short Beam Shear Strength (Avg. of 3 coupons)	14.8	13.0

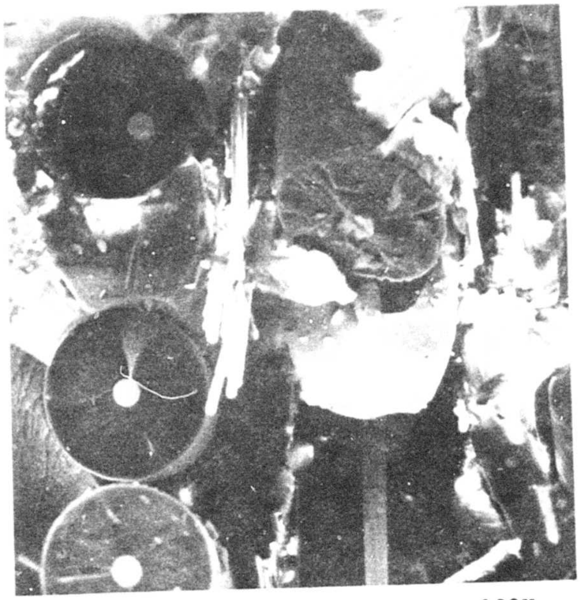


130X



230X

FIGURE 12. SEM ANALYSIS OF FRACTURE SURFACE OF $[0°/\pm45°/90°]_s$ 8-PLY COMPOSITE TENSILE COUPON - 74.0 KSI



130X

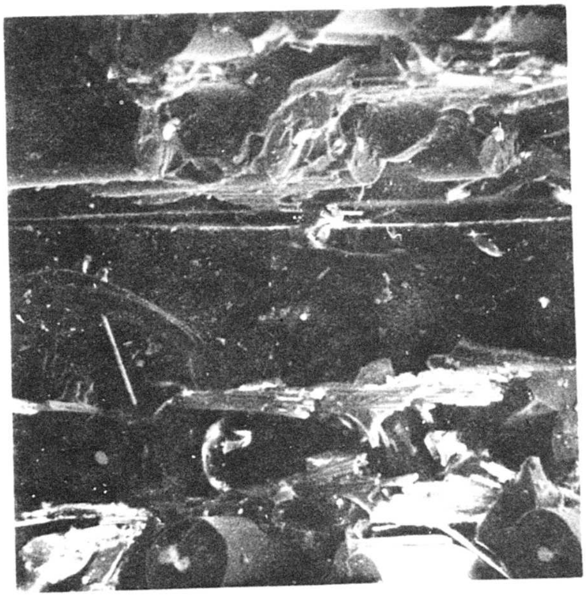


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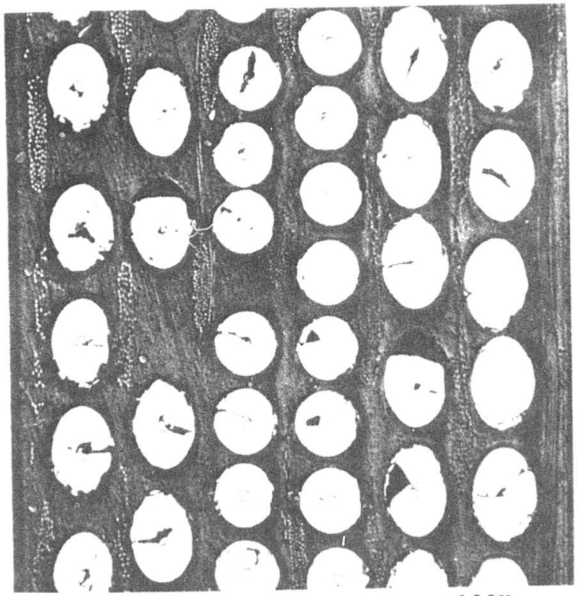
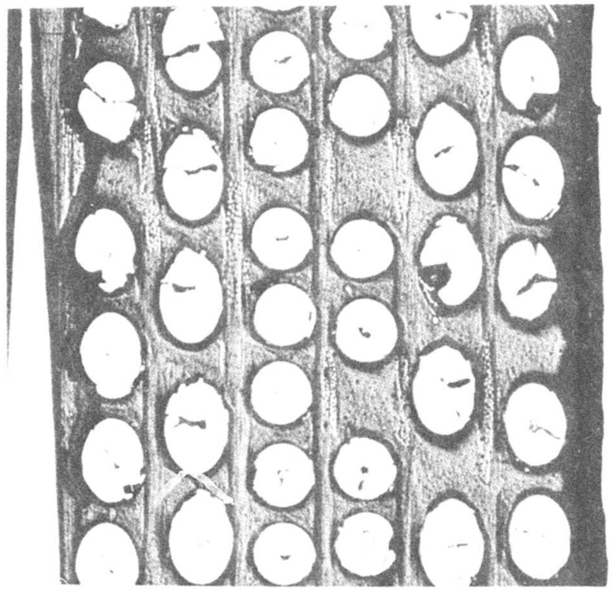
FIGURE 13. SEM ANALYSIS OF FRACTURE SURFACE OF $[0°/\underline{+}45°/90°]_s$ 8-PLY COMPOSITE TENSILE COUPON - 29.0 KSI



A. Cross Sectional Area
74.0 ksi Tensile Coupon



B. Cross Sectional Area
29.0 ksi Tensile Coupon

FIGURE 14. PHOTOMICROGRAPHS OF $[0°/\underline{+}45°/90°]_s$
8-PLY COMPOSITE TENSILE COUPONS

TABLE 45
ANGLEPLY
LONGITUDINAL TENSILE PROPERTIES
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
BATCH 57 - UNSTRESSED "RIGIDITE" 5505/4

ULT. TENSILE STR., KSI	STRAIN TO FAILURE, μIN/IN*	MODULUS, PSI x 10^6
25.8	3280	9.70
24.8	--	10.28
26.9	3500	9.29
24.8	3220	9.26
28.5	3620	9.78
29.2	3700	10.11
29.1	3880	10.57
27.7	4220	8.97
30.3	4400	9.16
29.6	4600	9.26

* All strains measured by extensometer

Two additional angleply laminates were cured from Batch 57. The mean longitudinal tensile strength of each (5 specimens tested from each laminate) was 26.2 ksi and 29.2 ksi. Both unidirectional and the angleply laminates were layed up using one ply of number 120 fiberglass bleeder per 8 plies of prepreg, and the same cure cycle was used. This cure cycle was as follows:

a. Bag at ambient temperature. Install in ambient temperature autoclave and apply vacuum to 24 inches Hg minimum. (Maximum Hg drop-off rate was 3.0 inches of Hg per minute).

b. Heat laminate to a temperature of 150F $\pm$5°F while maintaining a minimum pressure of 20 inches of Hg. When all laminate thermocouples reach 150F $\pm$5°F, simultaneously vent bag to atmosphere while increasing the positive pressure to 50 $\pm$5 psi. (Bag was not vented until positive pressure reached 10 psi [minimum]).

c. Increase laminate temperature to 340F $^{+10F}_{-0F}$ within 40 to 80 minutes at a rate of 4F to 8F per minute over the temperature range of 150F to 300F.

d. Maintain at a temperature of 350F $\pm$10F and a pressure of 45-55 psi for 90 $\pm$5 minutes.

e. Cool to below 125F in not less than 40 minutes before releasing pressure.

f. Post-cure all laminates in an air circulating oven at 375F-385F for 3 hours $\pm$10 minutes.

Causes for the low angleply properties were hypothesized as:

1. Problems in the layup and cure of composites.
2. Problems in mechanical testing.
3. Problems in saw cutting test coupons.

The most logical reason for the low angleply results seemed to be that the angleply laminate is much more sensitive to voids than is the unidirectional laminate. It seemed unlikely that errors in testing or machining could cause the severe degradation that was occurring. Tests were run on all hypotheses, however. Results showed that saw cutting the angleply laminates was the cause of the severe degradation in mechanical strength properties. Angleply properties are insensitive to major changes in processing, and the strength of individual specimens is independent of the size of the specimen and its gage length.

The experiments that were run to reach these conclusions are summarized here:

Effect of Saw Cutting on Angleply Tensile Strength

We hypothesized that cutting the angleply composite 90° to the 0° fiber direction might in some manner degrade composite properties. To test this hypothesis a series of experiments were run.

a. A 9-inch by 6-inch laminate was fabricated using cure process no. 1*. This laminate was saw cut as shown in Figure 15. The laminate was cut in half. The ends of one-half of the laminate were saw cut 90° to the 0° fiber direction before 1/2-inch wide tensile coupons were cut parallel to the 0° fiber direction. These

* Cure processes presented in the Appendix.

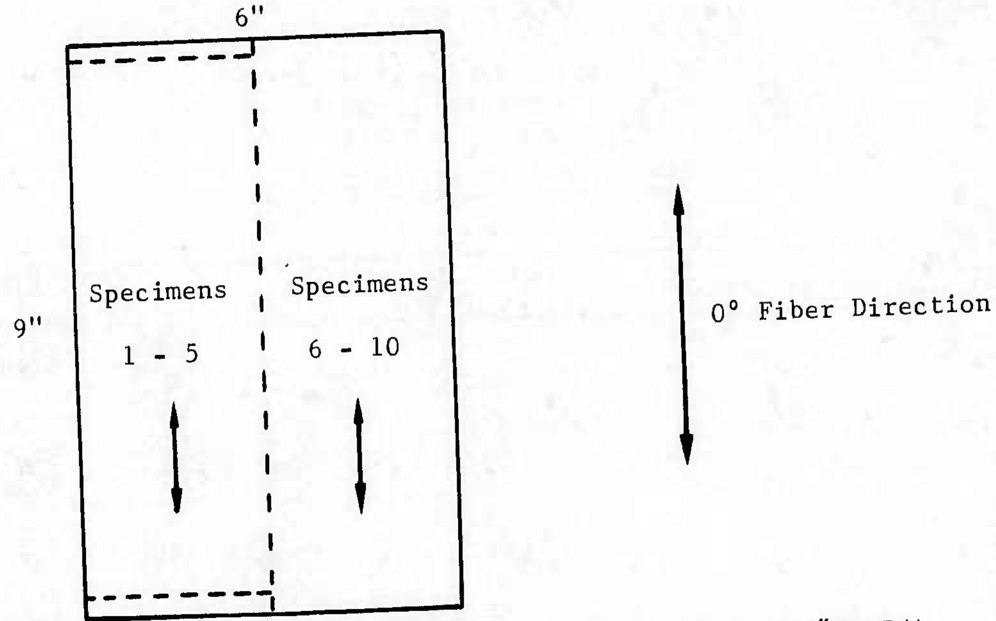


FIGURE 15. $[0°/\pm45°/90°]_s$ - 8-PLY LAMINATE -"RIGIDITE"5505/4
(Dashed lines represent saw cuts)

specimens were numbered 1 through 5. The ends of the second half of the laminate were not cut 90° to the 0° fiber direction. Tensile coupons 1/2-inch wide were cut the full 9-inch length parallel to the 0° fiber direction. These coupons were numbered 6 through 10. Test results on these coupons are tabulated in Table 46.

b. A 3-inch by 6-inch laminate was cured using cure process no. 2. This laminate was saw cut as shown in Figure 16. Test results for these coupons are tabulated in Table 47.

c. Two laminates each 11 inches by 6 inches were cured by cure process no. 3. The ends were saw cut off one laminate 90° to the 0° fiber direction. Tensile specimens 3/4-inch wide were cut parallel to the 0° fiber direction. These specimens were numbered 1 through 5. The ends on the second laminate were not saw cut. Tensile specimens were cut parallel to the 0° fiber direction the full 11-inch length of the composite. These coupons were numbered 6-10. Test results are tabulated in Table 48.

TABLE 46
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE PROPERTIES
9" x 6" ANGLEPLY LAMINATE
$[0°/\pm45°/90°]_s$ - 8-PLY
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ULT. STR., KSI	STRAIN TO FAILURE, μIN/IN
1	25.8	3280
2	24.8	--
3	26.9	3500
4	24.8	3220
5	28.5	3620
6	69.6	--
7	66.0	--
8	65.1	6820
9	66.0	6800
10	63.4	6720

* Specimens sawcut as shown in Figure 15.

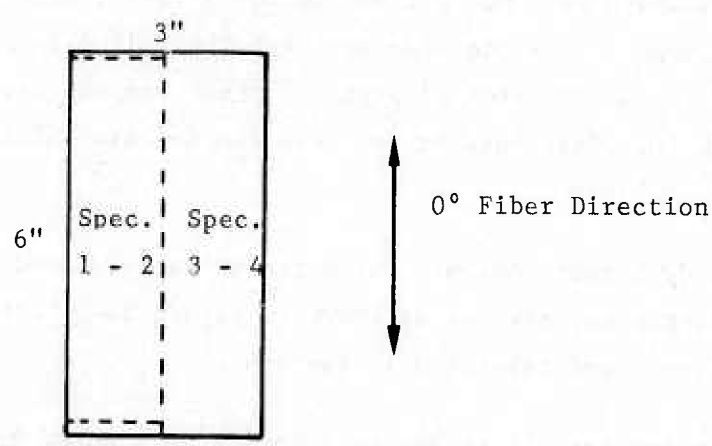


FIGURE 16. $[0°/\pm45°/90°]_s$ - 8-PLY LAMINATE - "RIGIDITE" 5505/4
(The dashed line represents saw cuts)

TABLE 47
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE PROPERTIES
3" x 6" ANGLEPLY LAMINATE
$[0°/\pm45°/90°]_s$ - 8-PLY
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ULT. STRENGTH, KSI
1	31.1
2	30.2
3	59.0
4	64.0

* Specimens sawcut as shown in Figure 16.

TABLE 48
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE PROPERTIES
11" x 6" ANGLEPLY LAMINATE
$[0°/\pm45°/90°]_s$ - 8-PLY
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ULT. STRENGTH KSI	STRAIN TO FAILURE
1	28.0	3160
2	25.4	2760
3	29.6	3710
4	28.4	3060
5	30.9	3890
6	66.0	7430
7	62.3	6850
8	67.7	7420
9	64.9	6800
10	64.9	6690

d. A 9-inch by 6-inch laminate was cured using cure process no. 3. This laminate was saw cut as shown in Figure 17. Test results are also shown in Figure 17.

e. A series of 6-inch by 3-inch laminates of seven different angleply orientations were fabricated and tested to determine if only specific ply orientations are degraded by saw cutting.

The experimental program was conducted in the following way:

1. All laminates were made from Roll 54, Batch 69 of "Rigidite" 5505/4 prepreg.

2. Two laminates, 6-inch by 3-inch, of each ply orientation were cured and postcured simultaneously to minimize processing variables. Cure process no. 3 was used.

3. The ends of one of each set of two laminates were saw cut off. Test specimens, 0.5-inch wide, were then saw cut from the panel. Test specimens were saw cut from the second panel without saw cutting the ends.

4. Tensile testing was conducted using a 2½-inch gage length on all specimens. Saw cut specimens were 5 inches by 0.5-inch; uncut specimens were 6-inches by 0.5-inch.

5. Five specimens were tested from each laminate.

A summary of results is presented in Table 49 . Experimental results are presented in Tables 50 through 56. The saw cutting experiments can be summarized as follows:

1. The degradative effect of saw cutting on the $[0°/\pm45°/90°]_S$ 8-ply laminate has been found to occur using two diamond cutting wheels. Five different operators have used these cutting wheels and found the same degradation to occur. The two cutting wheels used were: (1) an Avco-Felker Corporation Model 41-A with a 7-inch diameter blade, and (2) an Avco-Felker Corporation Model DH-1 with a 5-inch diameter blade.

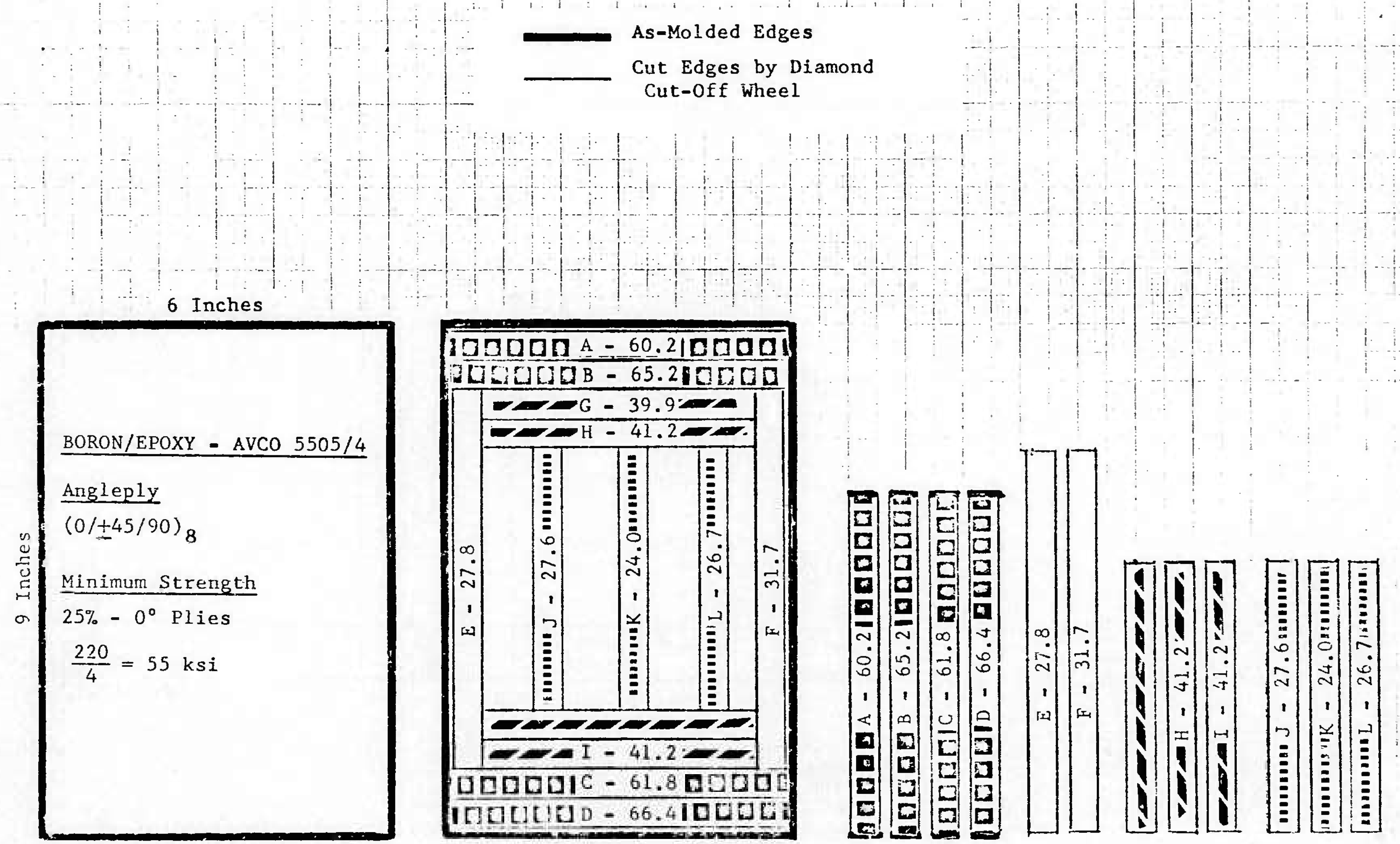


FIGURE 17. DESTRUCTION OF LONGITUDINAL TENSILE STRENGTH OF ANGLEPLY COMPOSITE BY DIAMOND CUT-OFF WHEEL MACHINING

TABLE 49

DEGRADATIVE EFFECT OF SAW CUTTING ON BORON/EPOXY COMPOSITES OF VARIOUS ORIENTATIONS UNSTRESSED "RIGIDITE" 5505/4

UNSTRESSED

PLY ORIENTATION	NO. PLIES	RATIO 0°/90° PLIES	ULT. TENSILE STR., KSI UNCUT	CUT	STR. REDUCTION DUE TO SAW CUTTING
$[0°]$	8	-	191	190	Not Statistically Significant
$[0°/90°]_s$	8	1/1	98.2	50.9	48%
$[0°/\pm45°/90°]_s$	16	1/1	51.9	27.0	48%
$[0°/\pm45°/90°]_s$	7	2/1	71.8	62.4	13%
$[0°/90°/0°_2(\pm45°)_2]_s$	16	3/1	84.4	64.4	24%
$[0°/\pm45°/0°/-45°]_s$	8	-	114	107	Not Statistically Significant
$[\pm45°/0°/\pm45°/\bar{0}°]_s$	11	-	64.7	60.7	Not Statistically Significant

TABLE 50
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 8-PLY UNIDIRECTIONAL LAMINATE
$(0°)_8$
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	201	190
2	204	196
3	197	206
4	178	192
5	176	168
Mean	191	190
Std. Deviation	13	14
Coeff. of Variation	6.8%	7.4%

TABLE 51
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 8-PLY ANGLEPLY LAMINATE
(90°/0°/90°/0°/0°/90°/0°/90°)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	94.1	50.0
2	100	51.0
3	94.3	50.0
4	95.2	48.6
5	111	54.8
Mean	98.2	50.9
Std. Deviation	7.2	2.4
Coeff. of Variation	7.3%	4.7%

TABLE 52
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 16-PLY ANGLEPLY LAMINATE
(0°/$\pm$45°/90°/0°/$\pm$45°/90°/90°/$\pm$45°/0°/90°/$\pm$45°/0°)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	52.3	27.9
2	54.6	27.4
3	50.0	26.7
4	45.4	26.3
5	57.3	26.7
Mean	51.9	27.0
Std. Deviation	4.5	0.6
Coeff. of Variation	8.7%	2.2%

TABLE 53
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 7-PLY ANGLEPLY LAMINATE
(0°/$\pm$45°/90°/$\pm$45°/0°)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	74.7	65.6
2	75.3	63.2
3	67.9	61.0
4	73.7	60.0
5	67.2	
Mean	71.8	62.4
Std. Deviation	3.9	2.5
Coeff. of Variation	5.4%	4.0%

TABLE 54
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 16-PLY ANGLEPLY LAMINATE
($0°/90°/0°/0°/\pm45°/\pm45°/\mp45°/\mp45°/0°/0°/90°/0°$)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	86.4	68.2
2	81.8	58.4
3	82.3	65.9
4	90.0	62.5
5	81.4	67.0
Mean	84.4	64.4
Std. Deviation	3.7	4.0
Coeff. of Variation	4.4%	6.2%

TABLE 55
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 8-PLY ANGLEPLY LAMINATE
($0°/+45°/0°/-45°/-45°/0°/+45°/0°$)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR., KSI
1	114	110
2	116	110
3	113	102
4	120	105
5	105	
Mean	114	107
Std. Deviation	6	4
Coeff. of Variation	5.3%	3.7%

TABLE 56
EFFECT OF DIAMOND SAW CUTTING ON
LONGITUDINAL TENSILE STRENGTH
6" x 3" 11-PLY ANGLEPLY LAMINATE
($\pm 45°/0°/\pm 45°/0°/\mp 45°/0°/\mp 45°$)
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	ENDS NOT CUT ULT. STR., KSI	ENDS CUT ULT. STR.,KSI
1	72.4	55.2
2	62.0	64.0
3	66.2	69.0
4	69.0	60.3
5	54.1	55.2
Mean	64.7	60.7
Std. Deviation	7.1	5.9
Coeff. of Variation	11.0%	9.7%

2. The degradative effect of saw cutting is somehow related to the 90° ply. Laminates without 90° plies are not degraded by saw cutting.

3. Increasing the thickness of composites which are degraded by saw cutting does not reduce the degradation. For example, the tensile strength of both 8- and 16-ply composites with the $[0°/\pm 45°/90°]_s$ orientation are reduced by 50 percent.

4. We have no explanation at this time for the degradative effect of saw cutting. A C-scan was run on a 6-inch by 3-inch laminate before and after sawcutting the ends. No change was apparent in the C-scan. The C-scans are shown in Figure 18.

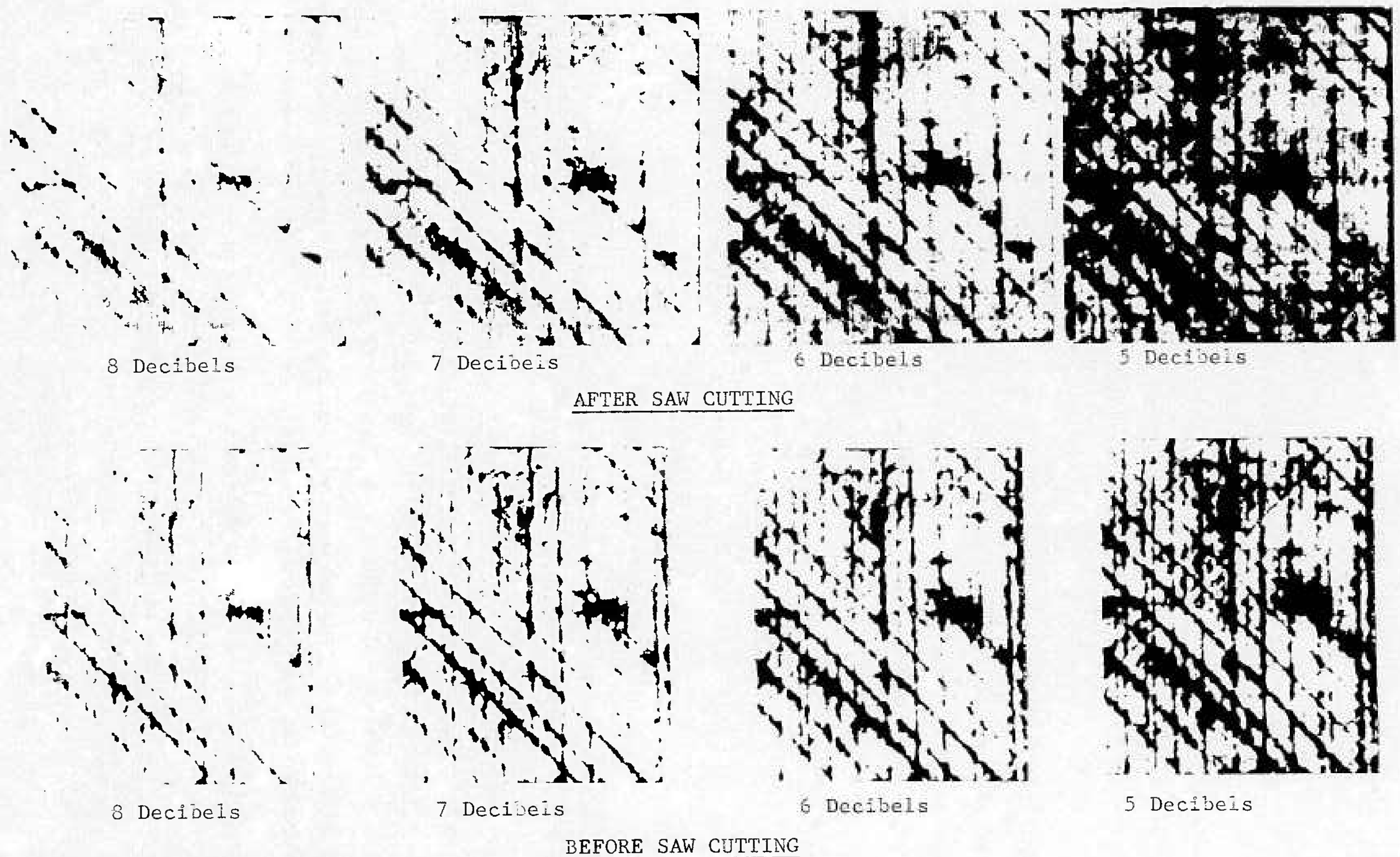


FIGURE 18. C-SCAN OF $[0°/\underline{+}45°/90°]_s$ 8-PLY LAMINATE BEFORE AND AFTER SAW CUTTING

Processing Studies

A variety of processing conditions were evaluated to help determine the cause of the strength degradation. A summary of variables tested is presented in Table 57. The processing variables studied were not the cause of the strength degradation. Both high (60-70 ksi) and low (25-40 ksi) strength results could be obtained from laminates cured by any procedure. The crucial operation was the way in which the laminate was sawed.

Evaluation of Mechanical Testing

All of the unidirectional and angleply tensile testing was conducted using coupons. There was no sandwich beam tensile testing. There appeared to be some possibility that the size of the tensile test coupon and its gage length had a significant effect upon tensile properties. The following coupons were evaluated:

0.5-inch by 6 inches
0.5-inch by 8 inches
0.5-inch by 9 inches
0.75-inch by 11 inches

Variations in the coupon dimensions had no effect upon strength or strain to failure.

To evaluate the effect of varying gage length on tensile properties the following experiments were run: a series of coupons were tested to failure. The broken sections of the coupons were regripped and tested to failure. This process was continued until the broken sections were too short to test. Note that the fractured coupons were <u>not</u> saw cut before retest. They were merely reinserted in the jaws and retested.

Varying the gage length from 8 inches to 1 inch had no effect on ultimate strength. These data are presented in Table 58. These data indicate that the specimen is "damaged" before the original test on the full length and the "damage" extends throughout the full length of the test specimen.

TABLE 57
PROCESSING VARIABLES STUDIED
"SPECIFICATION" GRADE "RIGIDITE" 5505/4

UNSTRESSED

BLEEDER PLIES	BLEEDER PLY RATIO (BLEEDER/PREPREG)	PRESSURE PLATE (0.064" Al)	TOTAL CURE PRESSURE (PSI)	TEMP. AT WHICH PRESSURE APPLIED (°F)	HEAT-UP RATE (°F/MIN.)	POSTCURE
112 Fiberglass	1/8	With	50	Ambient	4	None
116 Fiberglass	2/8	Without	65	135	6	3 Hrs.@375F
120 Fiberglass	3/8		100	150	10	4 Hrs.@375F
181 Fiberglass				175	18	16 Hrs.@375F
						24 Hrs.@375F

TABLE 58
EFFECT OF VARYING GAGE LENGTH ON
ANGLEPLY LONGITUDINAL TENSILE STRENGTH
$[0°/\pm45°/90°]_s$ - 8-PLY @ ROOM TEMPERATURE
UNSTRESSED "RIGIDITE" 5505/4

SPECIMEN NO.	GAGE LENGTH (INCHES)	LONGITUDINAL TENSILE STRENGTH, KSI
58B	8	65.8 (Original)
58B	5	62.1
58B	2½	66.8
58B	1.2	66.8
58A	8	67.0 (Original)
58A	2¼	59.9
62-1	8	61.7 (Original)
62-1	5	64.5
62-2	8	61.0 (Original)
62-2	5	63.6
62-3	8	61.2 (Original)
62-3	5	61.7
62-3	3½	65.2
62-3	2	61.7
62A	5	41.5 (Original)
62A	2¼	41.8
62B	5	32.1 (Original)
62B	2¼	40.3
A	8	21.7 (Original)
A	5¼	23.2
A	2-1/8	27.9
A	2-1/8	23.9
B	8	18.5 (Original)
B	5	26.4
B	3	27.1
B	2½	25.0

SECTION III

CONCLUSIONS

Five tasks were investigated in this program. These are listed below along with the conclusions reached for each.

1. Develop design allowable data to demonstrate improvements in mechanical properties and reduced property variation on "specification" grade and non-specification (defect) commercial grade boron prepreg and carbon substrate boron prepreg.

   Conclusions:

   a. "Specification" Grade "Rigidite" 5505/4 Boron Prepreg

   No improvements were realized in design allowable properties. It was concluded that the commercial grade boron prepreg is of such high quality that it cannot be improved by prestressing except in fatigue. The greatest potential for prestressing is with low-cost defect fibers.

   b. Carbon-Substrate Boron

   There was reduction in data scatter as well as improvement in some ultimate strengths. Fatigue life was reduced at high stress levels but not at low stress levels.

   c. Non-Specification (Defect) Boron Prepreg

   The strength of low-cost defect boron obtained for this program was not increased through prestressing during the preliminary processing studies. The concept of upgrading low-cost defect boron could not be validated, however, because of the limited type and quantity of defect boron available to the program. The basic concept is still considered valid and should be further evaluated.

2. Assess the economic impact of prestressing on boron/epoxy prepreg.

   Conclusions:

   A cost savings on boron prepreg cannot be realized at this time by prestressing defect prepreg tape.

3. Note fabrication areas which require modification in order to handle intentionally flawed material.

   Conclusions:

   Standard fabrication procedures can be used. No modifications are required.

4. Define prestressing levels.

   Conclusions:

   Optimum prestressing conditions were determined for each pre-prepreg used in the program. A prestress level equivalent to a 40-lb. load with prepreg going over rollers 0.450- to 0.575-inch in diameter covered the range of optimum values for all prepregs in this program.

It was found that certain ply orientations are extremely susceptible to degradation from saw cutting, which can lower mechanical properties by 50 percent. The nature of this degradation is unknown at this time.

SECTION IV

RECOMMENDATIONS

1. The work conducted on this program shows that prestressing high quality commercial grade boron/epoxy prepreg does not significantly improve or degrade composite properties except that in fatigue a large increase was produced by prestressing. For the manufacture of high quality prepreg, the incorporation of prestressing rollers into the manufacturing line might offer zero cost quality assurance to the prepreg. Random defects on the fibers would be eliminated.

   The possibility of prestressing low-cost "defect" boron fiber to improve it to the strength level of commercial fiber and thereby reduce material costs significantly cannot be ruled out from the results of this program. It is true that the "defect" fiber evaluated could not be improved by prestressing. However, this was really a one experiment test by Avco in producing "defect" fiber and Northrop's first experience in prestressing this type of fiber. Northrop's previous experience with low strength Hamilton Standard boron fiber showed it was possible to upgrade fiber properties substantially. We recommend that further consideration be given to the concept of improving low-cost "defect" fiber by prestressing.

2. The unexpected result found on this program that saw cutting procedures standard to the industry can seriously degrade mechanical properties of certain angleply composites should be thoroughly investigated. The cause of the degradation should be determined and means to prevent the degradation established.

APPENDIX

APPENDIX

A. FABRICATION OF LAMINATES

Three procedures, each standard in the industry, were used to cure laminates during this program. The procedures are summarized in Table A-1.

B. MACHINING OF LAMINATES

All laminates were machined using Avco-Felker Corporation Diamond Cutting Wheels. Two wheels were used: Model 41-A which has a 7-inch diameter wheel, and Model DH-1 with a 5-inch diameter blade. The laminates were fed into the blade at a rate of 1-4 feet per minute. Water was used as a coolant.

C. MECHANICAL TESTING PROCEDURES

Table A-2 shows the geometries of the coupons used for mechanical testing. Strains to failure were measured using both strain gages and extensometers. The type of instrumentation used is summarized in Table A-3.

Diagrams of the rail shear specimen is shown in Figures A-1. Testing was done on both a 10,000-lb. Instron Universal Testing Machine and a 120,000-lb. Baldwin Testing Machine. A summary of the test machines used and the head speeds which were used for the individual tests are summarized in Table A-4.

D. FIBER TESTING PROCEDURES

A six-inch length of the three-inch wide prepreg was soaked in either methyl ethyl ketone or tetrohydrofuran to dissolve the resin. The six-inch lengths of fiber were separated from the scrim cloth, spread out, and allowed to air dry. One hundred of the approximately 600 fibers were selected at random and tested in a 1,000-lb. Instron test machine.

TABLE A-1. PROCESSING CONDITIONS FOR UNIDIRECTIONAL AND ANGLEPLY LAMINATES

	CURE PROCEDURE NUMBER 1	CURE PROCEDURE NUMBER 2	CURE PROCEDURE NUMBER 3
CUTTING OF PLIES	Plies cut to size with template using Stanley knife on hard table	Plies marked with pencil using template, then cut with scissors	Straight strips cut oversize using razor and template on soft rubber base
ALIGNING PLIES	No light table	No light table	Used light table
RELEASE BETWEEN CAUL PLATE AND LAMINATE	Non-porous Teflon-coated fiberglass sheet	Non-porous Teflon-coated fiberglass sheet	Liquid parting agent Ram 225
DAM MATERIAL	1/8" x 1" Silicone rubber	1/8" x 1" Silicone rubber	1/16" x 1" Cork
SEPARATOR BETWEEN	Porous Teflon-coated fiberglass	Porous Teflon-coated fiberglass	Porous Teflon-coated fiberglass with 1" long slits 1/2" apart
BLEEDER MATERIAL	1 Ply 120 fiberglass	1 Ply 112 fiberglass	3 Plies 112 fiberglass
COVERING OVER BLEED PLIES	Non-porous Teflon-coated fiberglass	Non-porous Teflon-coated fiberglass	Non-porous Teflon coated fiberglass slit at each of the four corners
PRESSURE PLATE	.065" Aluminum	.085" Aluminum	None
BREATHER PLIES	Osnaburg cloth	2 Plies Osnaburg cloth	1 Ply 181 fiberglass
VACUUM BAG	Nylon envelope bagged	Nylon positioned on caul plate	Nylon positioned on caul plate

TABLE A-1. PROCESSING CONDITIONS FOR UNIDIRECTIONAL AND ANGLEPLY LAMINATES (Continued)

	CURE PROCEDURE NUMBER 1	CURE PROCEDURE NUMBER 2	CURE PROCEDURE NUMBER 3
VACUUM BAG SEALANT	Zinc chromate	Zinc chromate	Zinc chromate
CURE PRESSURE	50 psi air, bag vented at 150F	85 psi air, bag vented at R.T.	50 psi air, bag vented at 135F
AUTOCLAVE SIZE	6 ft. dia. x 12 ft.	1 ft. dia. x 3 ft.	6 ft. dia. x 12 ft.
HEAT-UP RATE	9°F/min. circulating air	12°F/min. static air	6°F/min. circulating air
CURE TIME AT TEMPERATURE	90 min. at 350F	90 min. at 350F	90 min. at 350F
COOL DOWN	To 150F under pressure	To 150F under pressure	To R.T. under pressure
POST CURE	375F for 3 hrs.	R.T. to 375F in 15-20 min. Hold at 375F for 3 hrs.	R.T. to 375F in 15-90 min. Hold at 375F for 4 hrs.

TABLE A-2
SPECIMEN GEOMETRY

TEST	SPECIMEN THICKNESS	WIDTH	LENGTH	TABS
Unidirectional Longitudinal Tension (Static & Fatigue)	8 plies	1/2-inch	9 inches	Fiberglass
Unidirectional 90° Transverse Tension	15 plies	1 inch	9 inches	None
$[0°/\pm45°/90°]_s$ Longitudinal Tension	8 plies	3/4-inch	11 inches	Peel Ply
Unidirectional Longitudinal Compression (Sandwich Beam)	8 plies	1 inch	22 inches	None
$[0°/\pm45°/90°]_s$ Rail Shear	16 plies	3 inches	6 inches	None

E. FATIGUE TESTS

Specimen geometry:

Thickness: 8 plies

Width: 0.5-inch

Length: 9 inches

Nominal Area: 0.02-in.^{2}

Tabs: Fiberglass

Test machine: Sonntag Universal Fatigue Testing Machine.

Load Requirements: Tension-tension fatigue, 1800 cpm test frequency, stress ratio = 0.1

Environment: In air at ambient temperature.

TABLE A-3
INSTRUMENTATION USED TO MEASURE
STRAIN TO FAILURE

TEST	TEST TEMP.	INSTRUMENTATION	
		EXTENSOMETER	STRAIN GAGE*
0° Tensile	R.T.	Instron G51-13A Strain Gage Extensometers	EA06-250BF-350**
0° Tensile	350F	"	"
90° Tensile	R.T.	"	"
$[0°/\pm 45°/90°]_s$	R.T.	"	"
$[0°/\pm 45°/90°]_s$	350F	"	"
0° Compression	R.T.	None	EA06-090DG-120***
0° Compression	350F	None	"
$[0°/\pm 45°/90°]_s$ Rail Shear	R.T.	None	EA06-125TD-120
0° Tensile Fatigue	R.T.	None	None

* All gages are Micro-Measurements Brand

** Poisson's = EA06-125TF-120

*** Poisson's = EA06-125TA-120

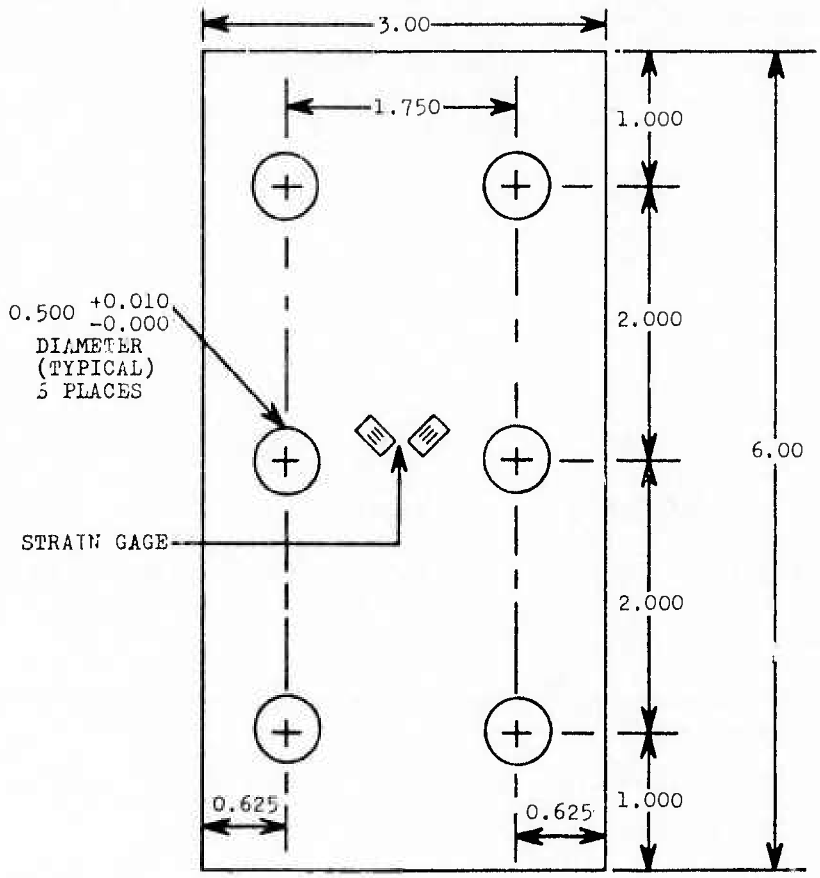


FIGURE A-1. RAIL SHEAR SPECIMEN

TABLE A-4
TEST MACHINES AND
OPERATING CONDITIONS

TEST	TEST MACHINE	HEAD SPEED
Unidirectional		
Longitudinal Tension	Instron Universal Testing Machines (10,000 lb.)	0.5-in/mil
Transverse Tension	"	"
Longitudinal Compression	"	"
Angleply $[0°/\pm45°/90°]_s$	"	"
Longitudinal Tension	"	"
Rail Shear	Baldwin Testing Machine (120,000 lb.)	"

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